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Standard Form 298 (Rev. 8-98)
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23031248 TP-FY99-0110

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✓ DTS

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MEMORANDUM FOR PRR (Contractor/In-House Publication)

FROM: PROI (TI) (STINFO)

1 June 1999

SUBJECT: Authorization for Release of Technical Information, Control Number: **AFRL-PR-ED-TP-FY99-0110**
Fajardo and Tam, "High Resolution Infrared Absorption Spectroscopy of Molecular Dopants in Cryogenic Solid
Parahydrogen"

(Public Release)

Poster Session HEDM CONFERENCE

High Resolution Infrared Absorption Spectroscopy of Molecular Dopants in Cryogenic Solid Parahydrogen

Mario E. Fajardo and Simon Tam

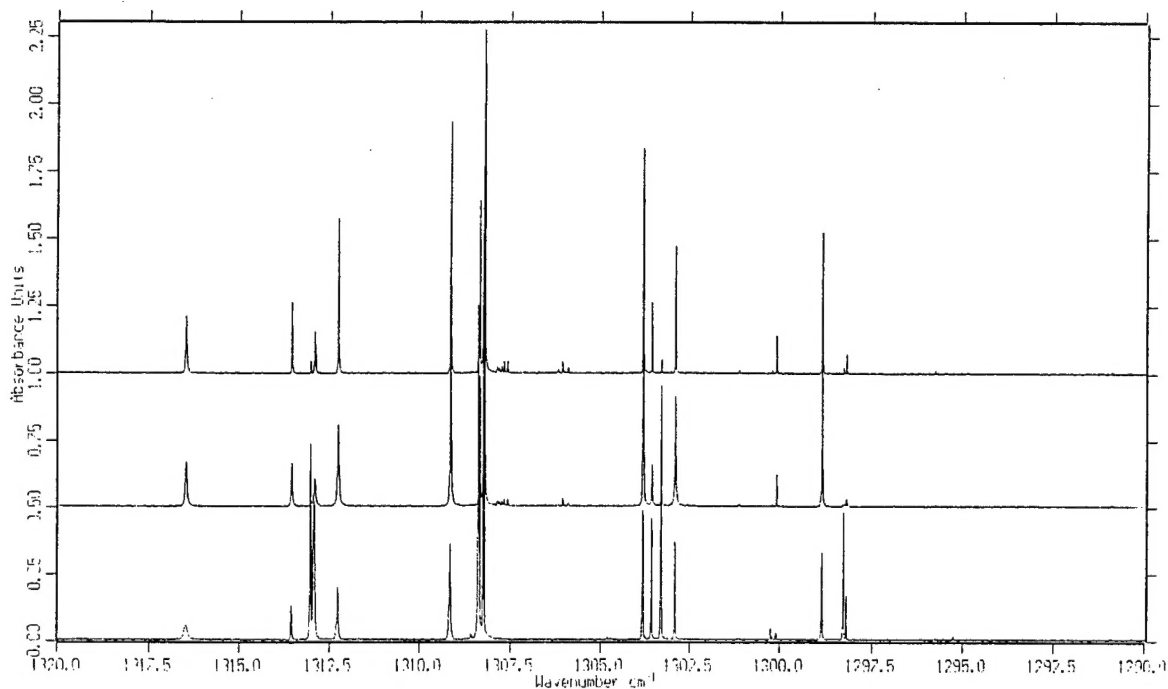
US Air Force Research Laboratory, Propulsion Directorate
(AFRL/PRSP Bldg. 8451, Edwards AFB, CA 93524-7680) mario_fajardo@ple.af.mil

Premature claims of successful energy storage in cryogenic solids date back to the National Bureau of Standards' Free Radicals program. Such errors typically result from reliance on unsupplemented calorimetric data, which shed little light on the mechanism of energy storage, *i.e.*, chemical identities of the energetic species and microscopic structures within the trapping medium. **Only spectroscopic measurements provide the species and structure specific information required for directed incremental progress towards higher stored energy densities.**

In HEDM program funded studies, Oka and co-workers pioneered the use of high resolution spectroscopic techniques in solid parahydrogen (pH₂). Our rapid vapor deposition sample preparation technique now enables us to trap virtually any volatilizable species in solid pH₂. We present results of high resolution infrared absorption experiments on pH₂ solids doped with isolated molecules and small clusters.

DISTRIBUTION STATEMENT A
Approved for Public Release
Distribution Unlimited

13 PPM CH₄/pH₂ d \approx 3mm



st27011.8 annealed T=2.4K
st27011.4 annealing T=4.8K
st27011.2 as deposited T=2.4K

resolution = 0.0075 cm⁻¹

20021121 033

OBJECTIVE

Develop infrared (IR) absorption spectroscopic diagnostics for HEDM doped cryogenic parahydrogen (pH₂) solids.

APPROACH

Collect high resolution IR spectra of pH₂ solids doped with non-energetic species: prototypical diatomic, triatomic, linear polyatomic, symmetric top, and spherical top dopant molecules.

Model data as "matrix-perturbed" gas phase spectra, if possible. Develop new spectroscopic models in collaboration with AFRL/Edwards Theory group, as necessary.

2 Surveys

SUMMARY

Many, but not all, molecular dopants exhibit very sharp (~ 0.01 cm⁻¹ FWHM) IR absorption lines in solid pH₂, providing an extremely detailed window into trapping site structures and dynamics.

Model for spherical top molecules trapped in single substitutional sites in fcc and hcp solid pH₂ developed in collaboration with Prof. T. Momose of Kyoto U. is completely successful in explaining spectra of CH₄/pH₂ system. Model of trapped diatomic molecules forthcoming.

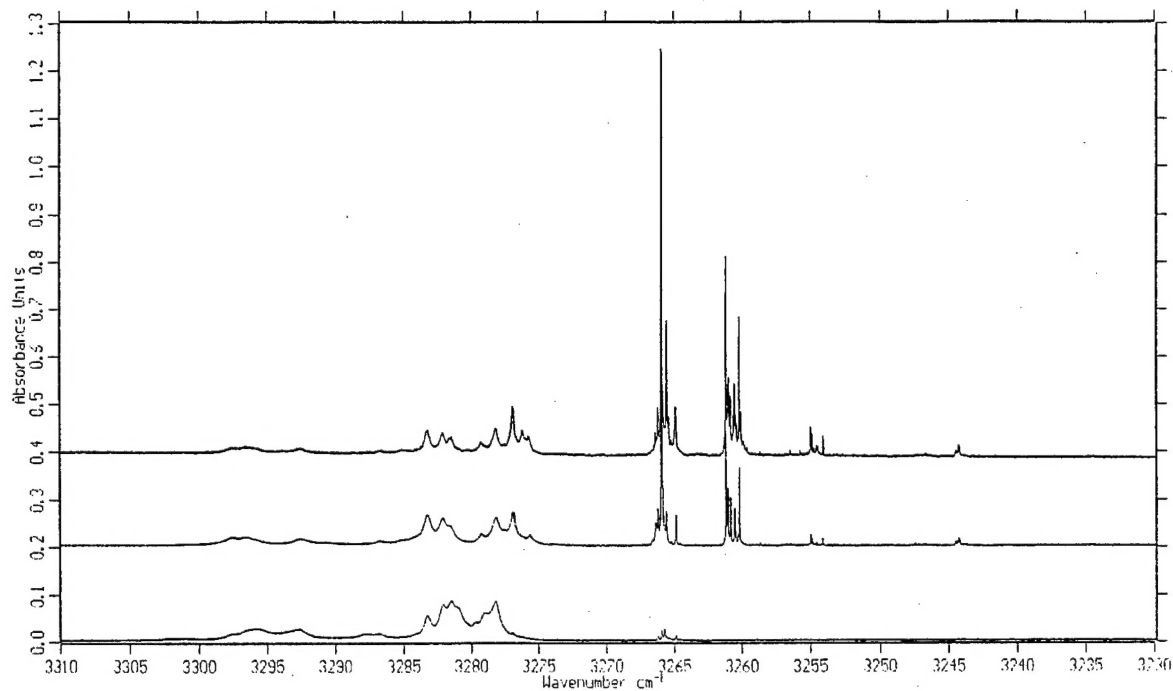
FUTURE DIRECTIONS

Develop model for dopants trapped in multi-substitutional vacancies.

Include effects of lattice relaxation via quantum Monte Carlo methods.

Back

^{ppm}
9 PPM C₂H₂/pH₂ d≈3mm

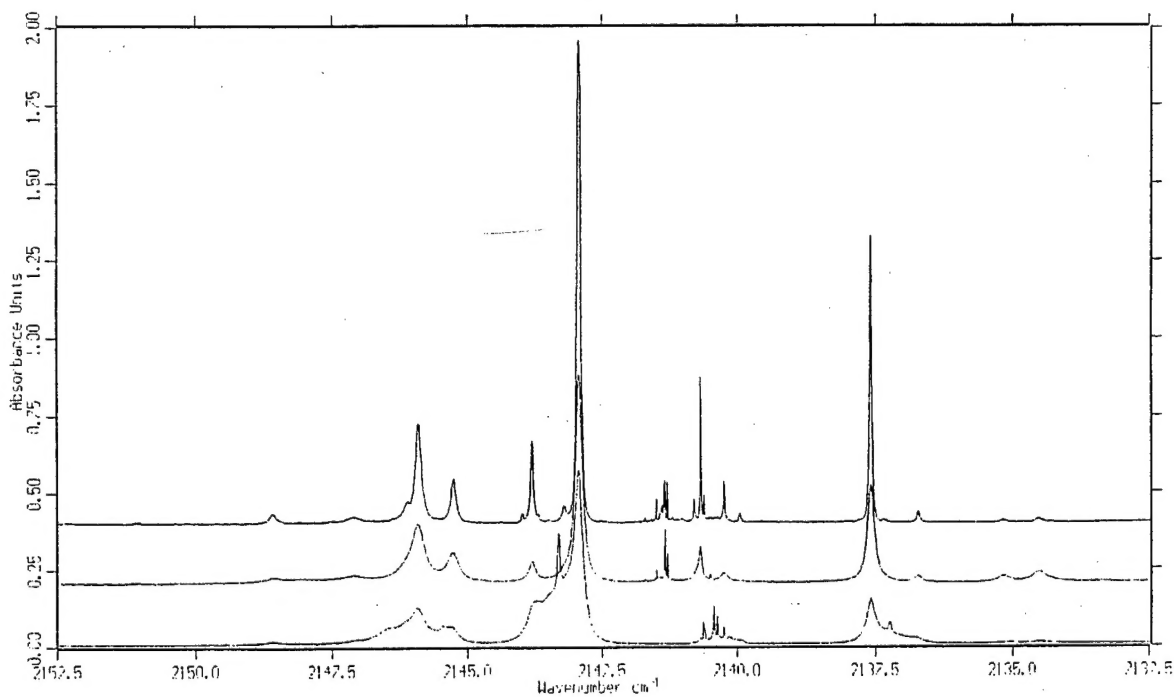


st28034.13 annealed T=2.4K
st28034.7 annealing T=4.8K
st28034.5 as deposited T=2.4K

resolution = 0.005 cm⁻¹

ST28034.5

^{ppm}
13 PPM CO/pH₂ d≈3mm

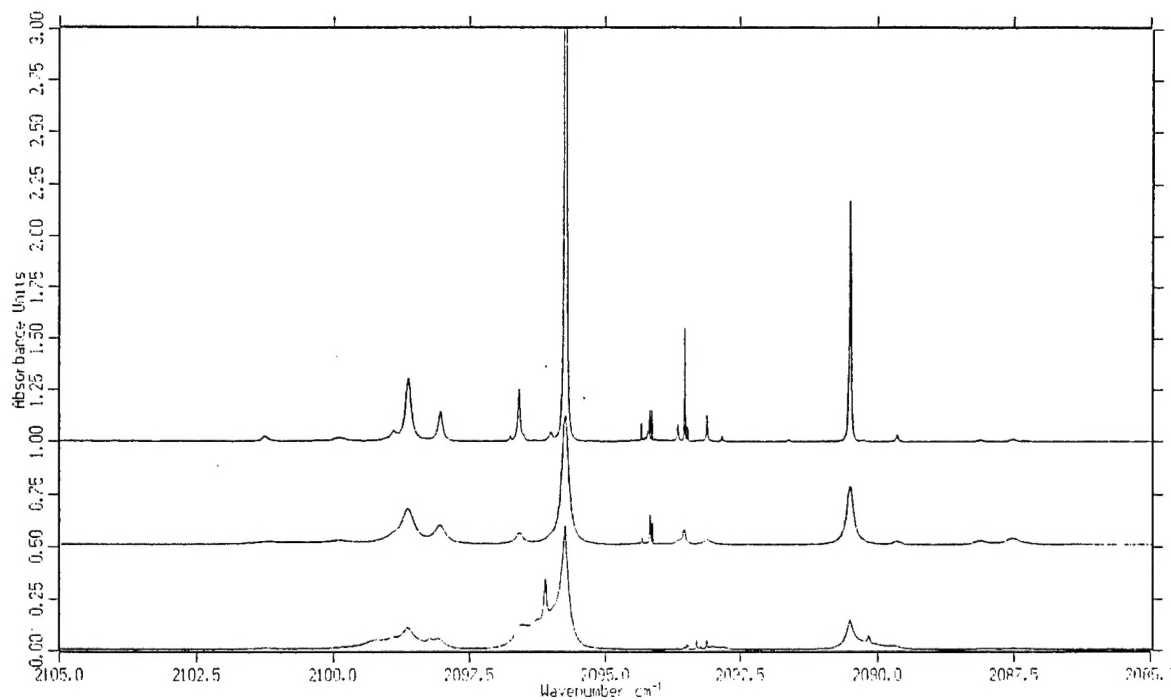


st27017.18 annealed T=2.4K
st27017.14 annealing T=4.8K
st27017.10 as deposited T=2.4K

resolution = 0.0075 cm⁻¹

ST27017.10

$^{13}\text{C}^{16}\text{O}/\text{pH}_2$ $d \approx 3\text{mm}$

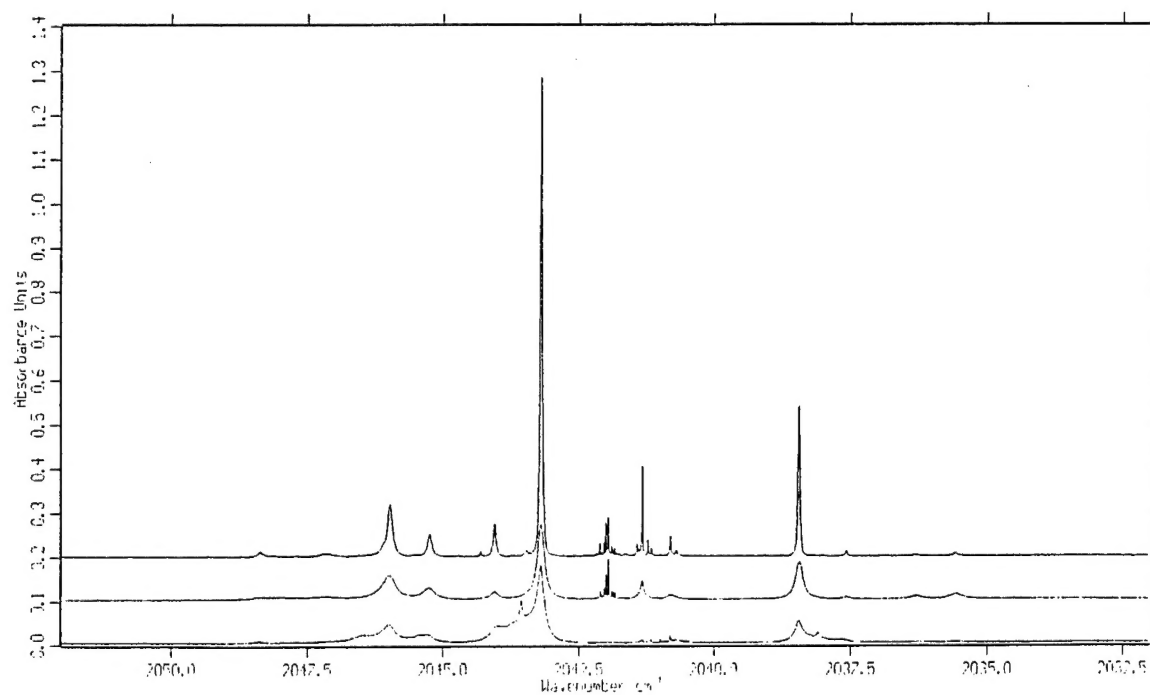


st28082.6 annealed T=2.4K
 st28082.4 annealing T=4.8K
 st28082.2 as deposited T=2.4K

11 PPM $^{13}\text{CO}/\text{pH}_2$ resolution = 0.005 cm^{-1}

ST28082.2

$^{13}\text{C}^{18}\text{O}/\text{pH}_2$ $d \approx 3\text{mm}$

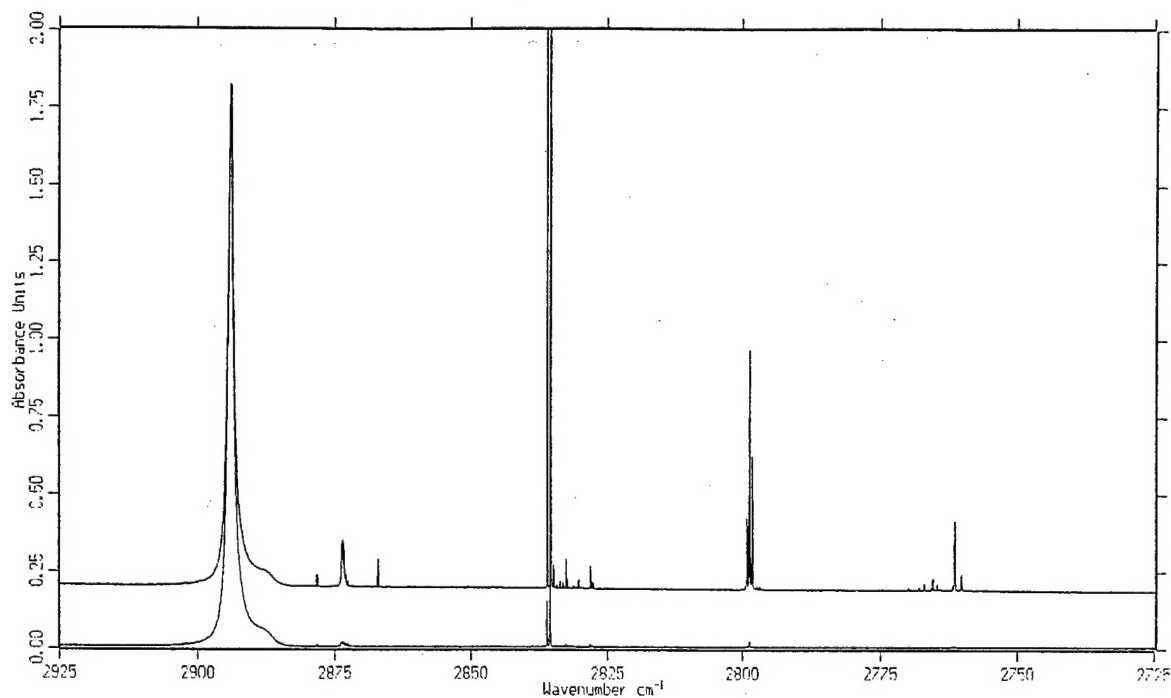


st28085.5 annealed T=2.4K
 st28085.3 annealing T=4.8K
 st28085.1 as deposited T=2.4K

29 PPM $^{13}\text{CO}/\text{pH}_2$ resolution = 0.005 cm^{-1}

ST28085.1

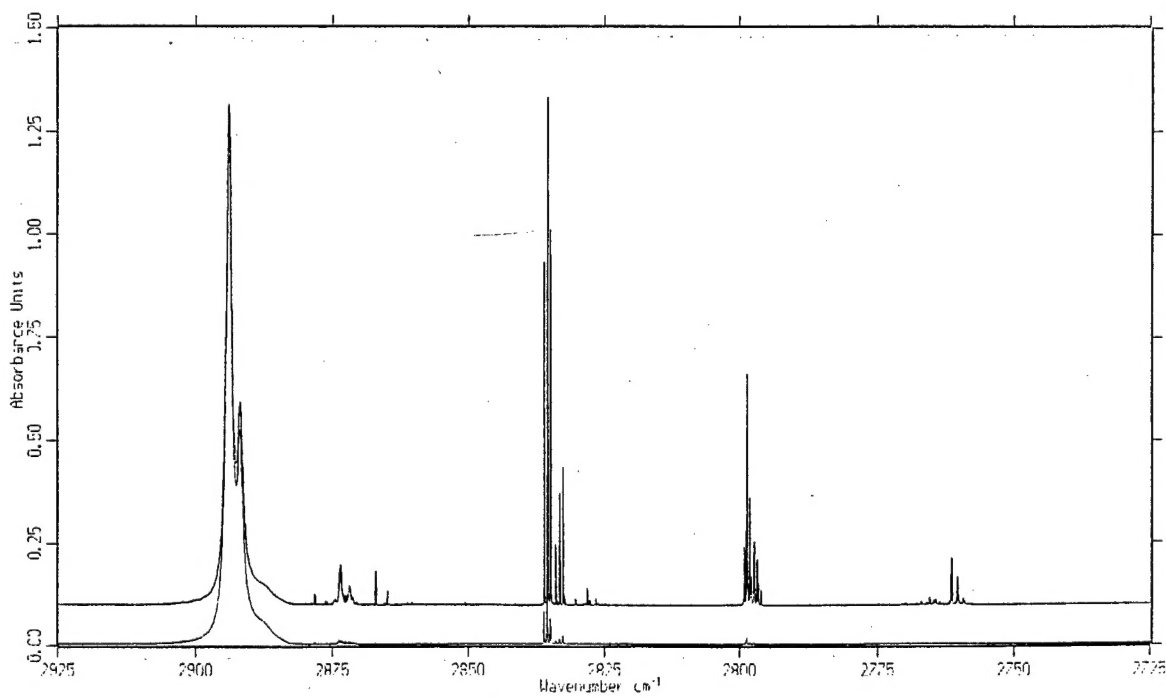
ppm
90 PPM $\text{H}^{35}\text{Cl}/\text{pH}_2$ $d \approx 3\text{mm}$



st27079.11 annealed $T=2.4\text{K}$
st27079.7 as deposited $T=2.4\text{K}$
resolution = 0.005 cm^{-1}

st27079.7

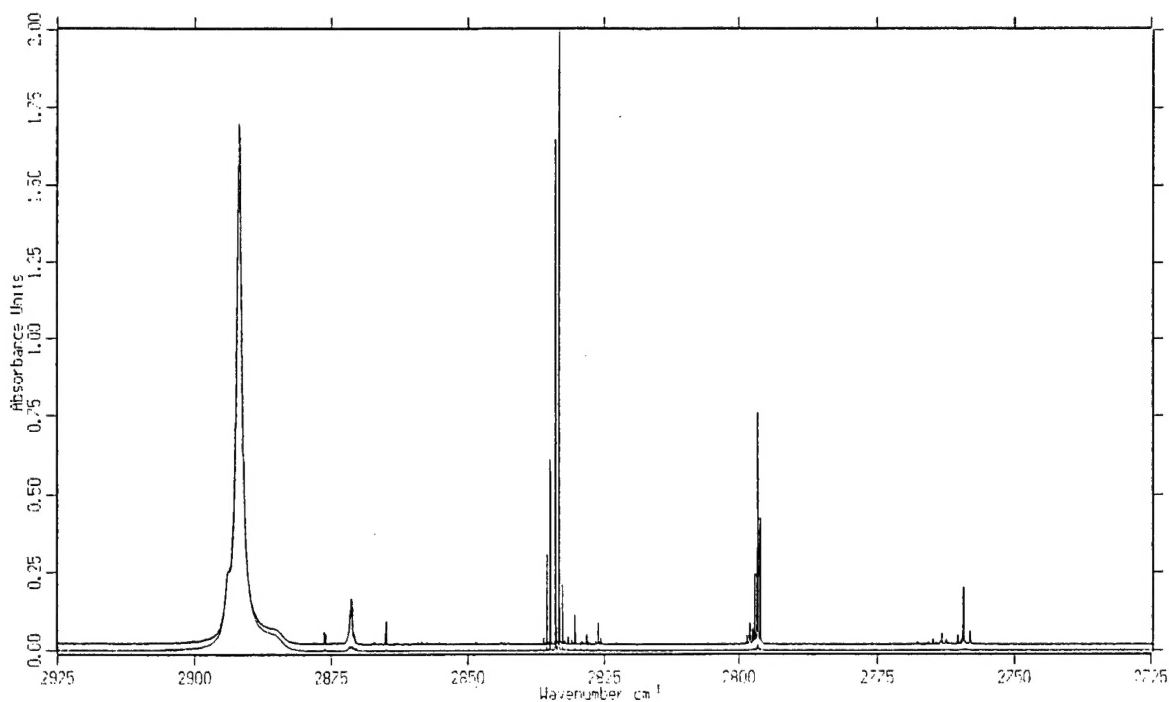
ppm
88 PPM HCl/pH_2 $d \approx 3\text{mm}$



st27061.11 annealed $T=2.4\text{K}$
st27061.7 as deposited $T=2.4\text{K}$
resolution = 0.0075 cm^{-1}

st27061.7

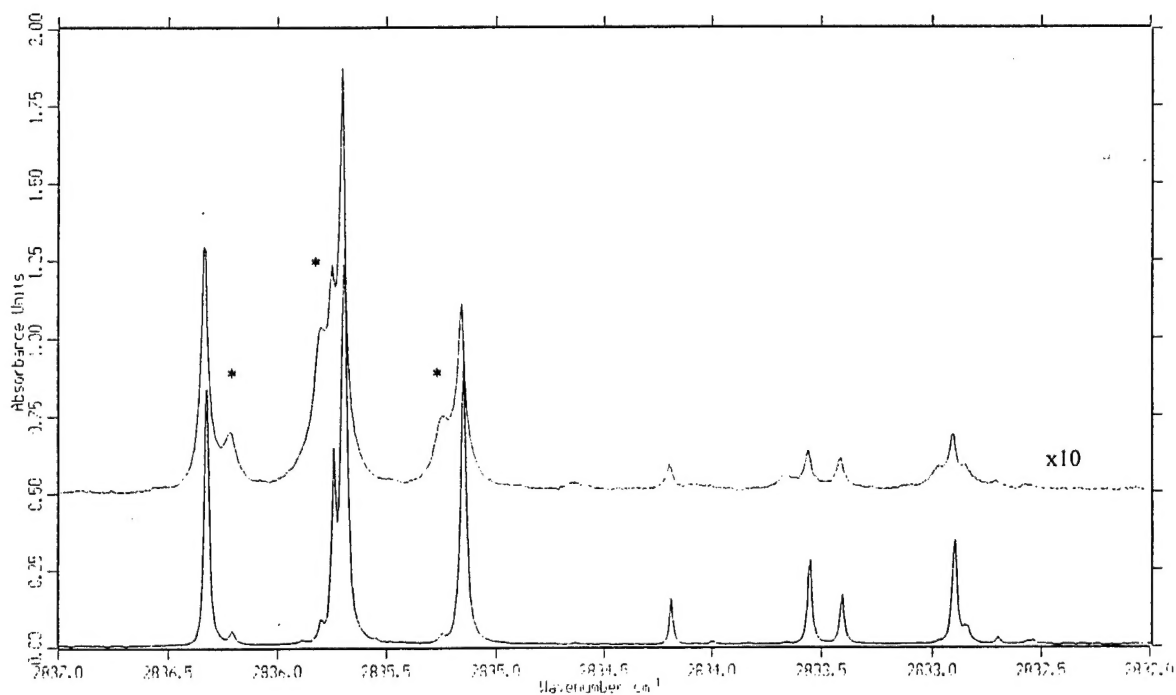
94 PPM ³⁷Cl/pH₂ d≈3mm



st27103.6 annealed T=2.4K
st27103.2 as deposited T=2.4K
resolution = 0.005 cm⁻¹

st27103.2

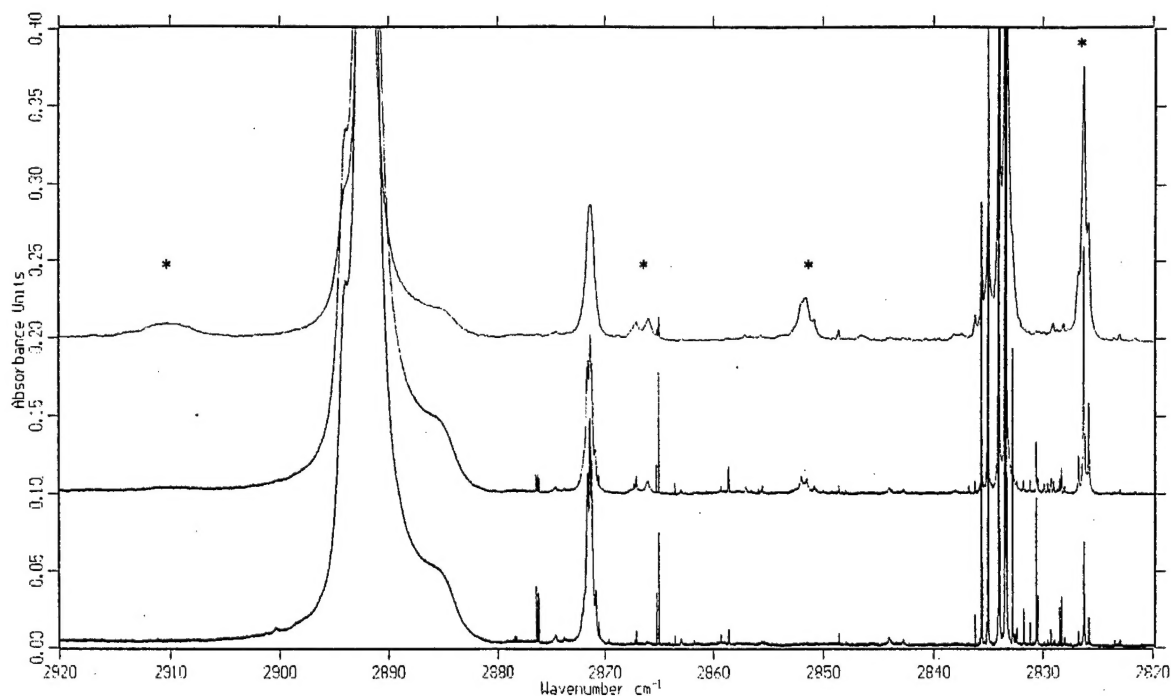
irreversible T dependences



88 PPM HCl/pH₂ d≈3mm
st27061.7 as deposited T=2.4K
st27061.11 annealed T=2.4K

st27061.11

reversible T dependences

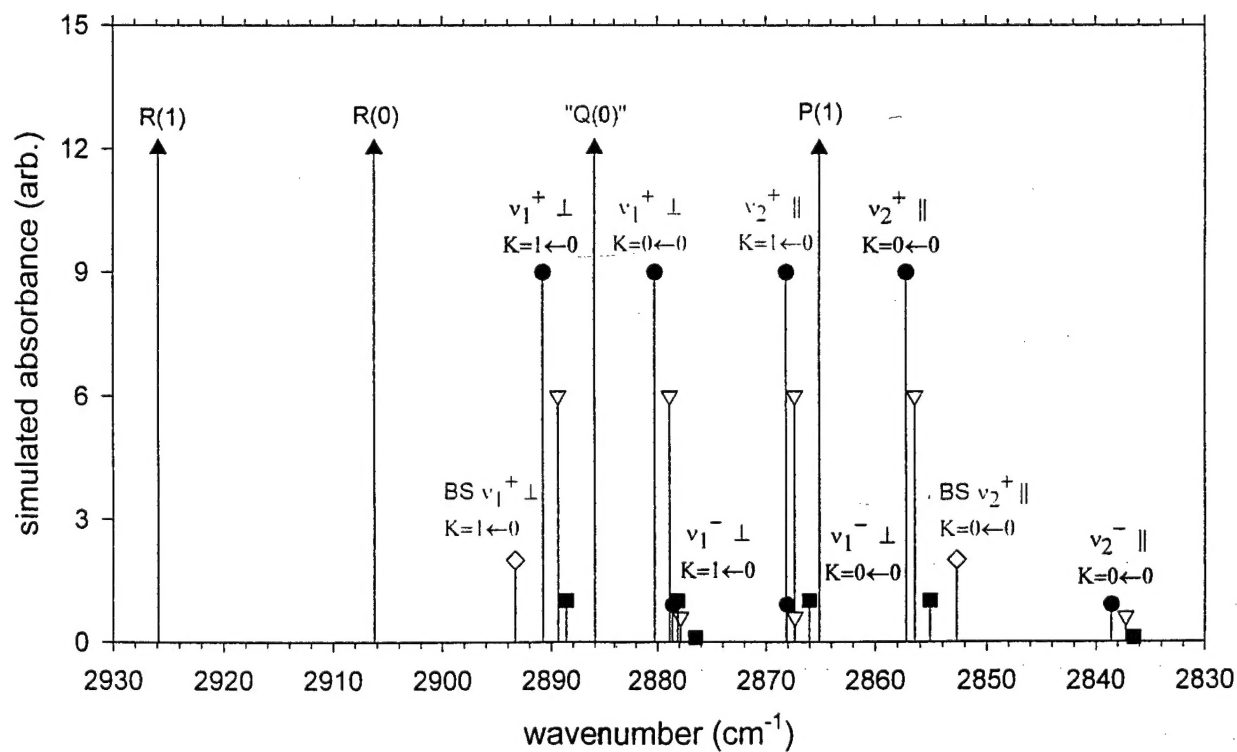


st27103.13 evaporating $T \approx 10K$
 st27103.4 annealing $T = 4.8K$
 st27061.11 annealed $T = 2.4K$

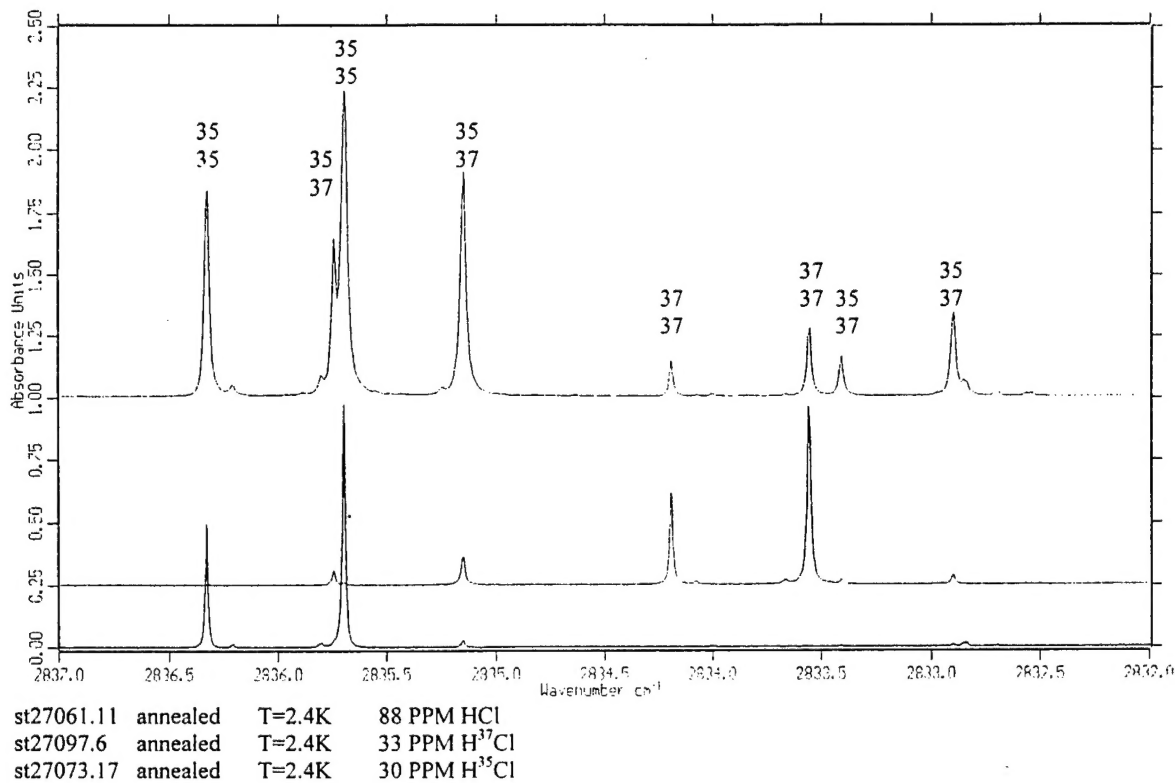
94 PPM $H^{37}Cl$

st27103.4

gas phase HCl and $(HCl)_2$ transitions

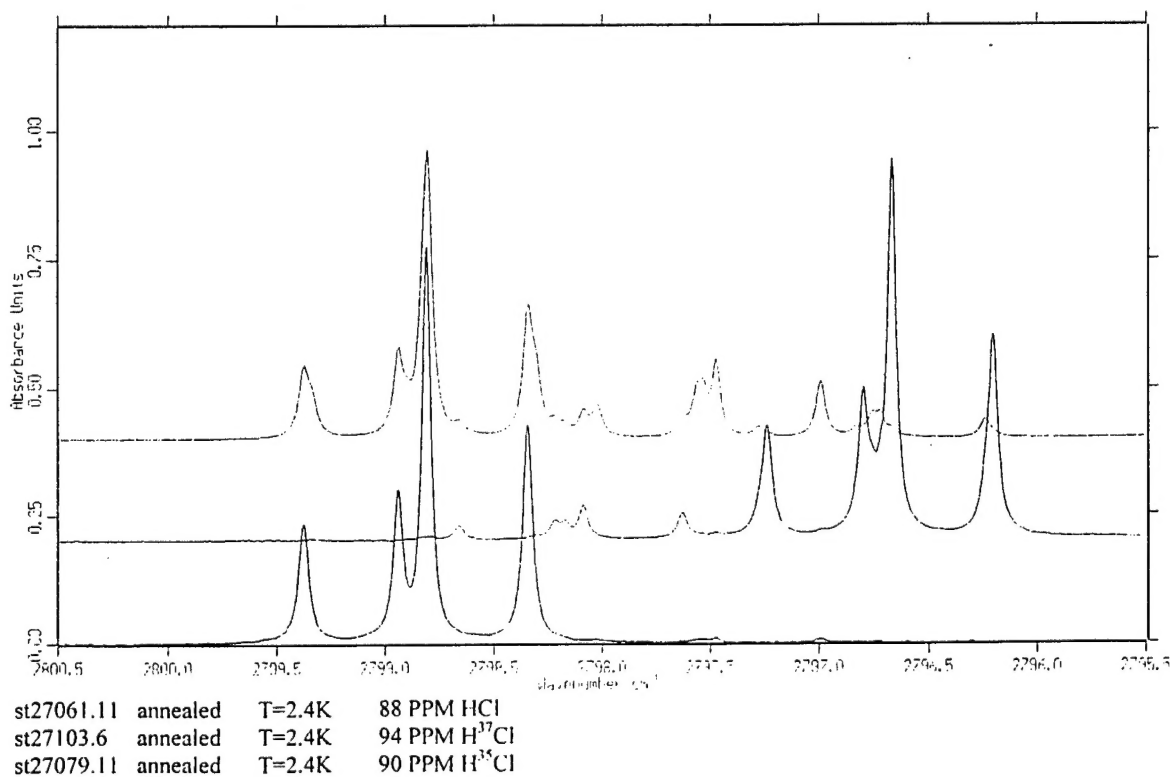


$(\text{HCl})_2 \nu_2^+$ region

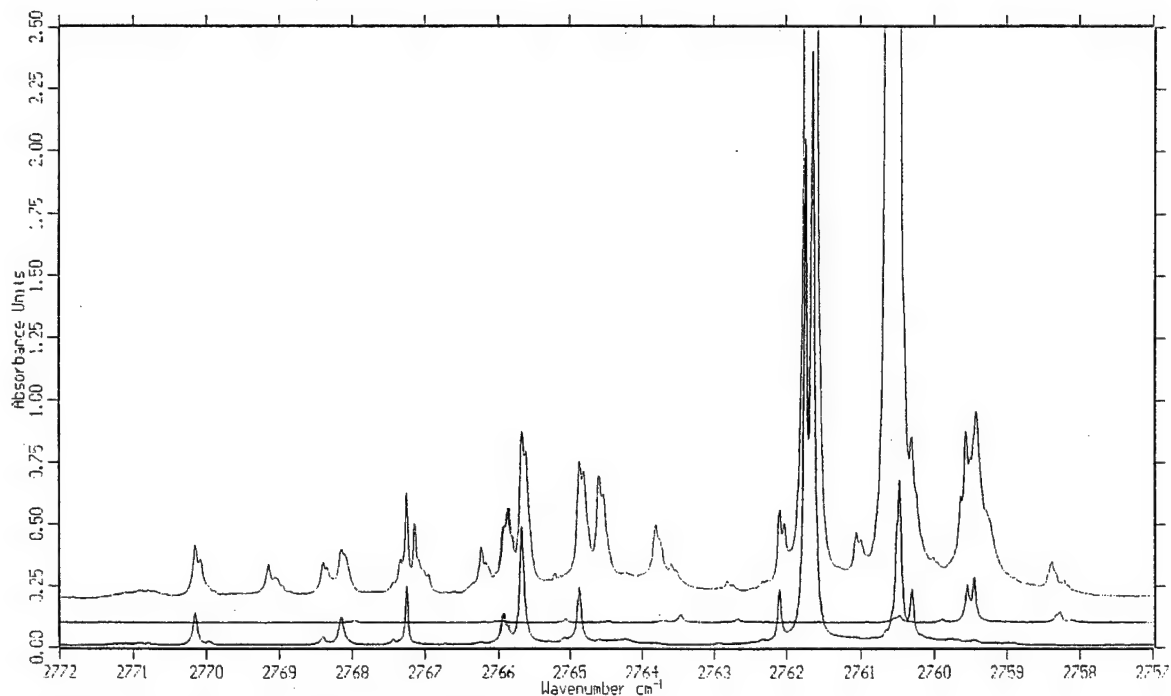


st27073.17

$(\text{HCl})_3$



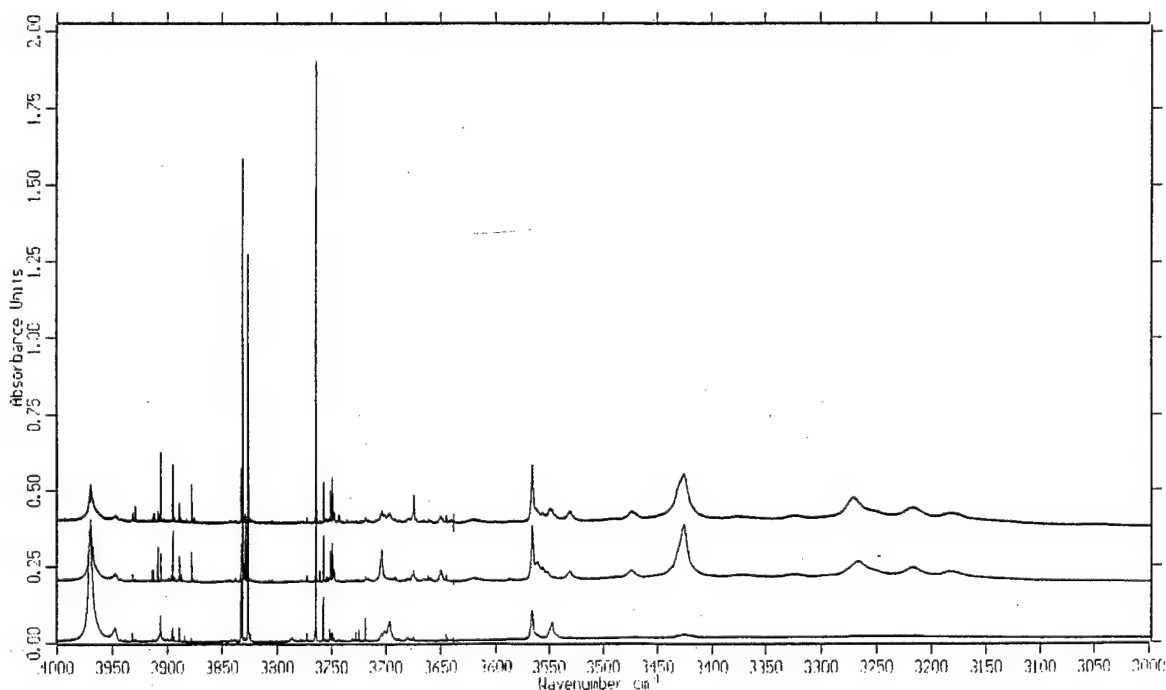
st27103.6



st27067.10 annealed T=2.4K 494 PPM HCl
 st27103.6 annealed T=2.4K 94 PPM H³⁷Cl
 st27085.9 annealed T=2.4K 284 PPM H³⁵Cl

ST27103.6

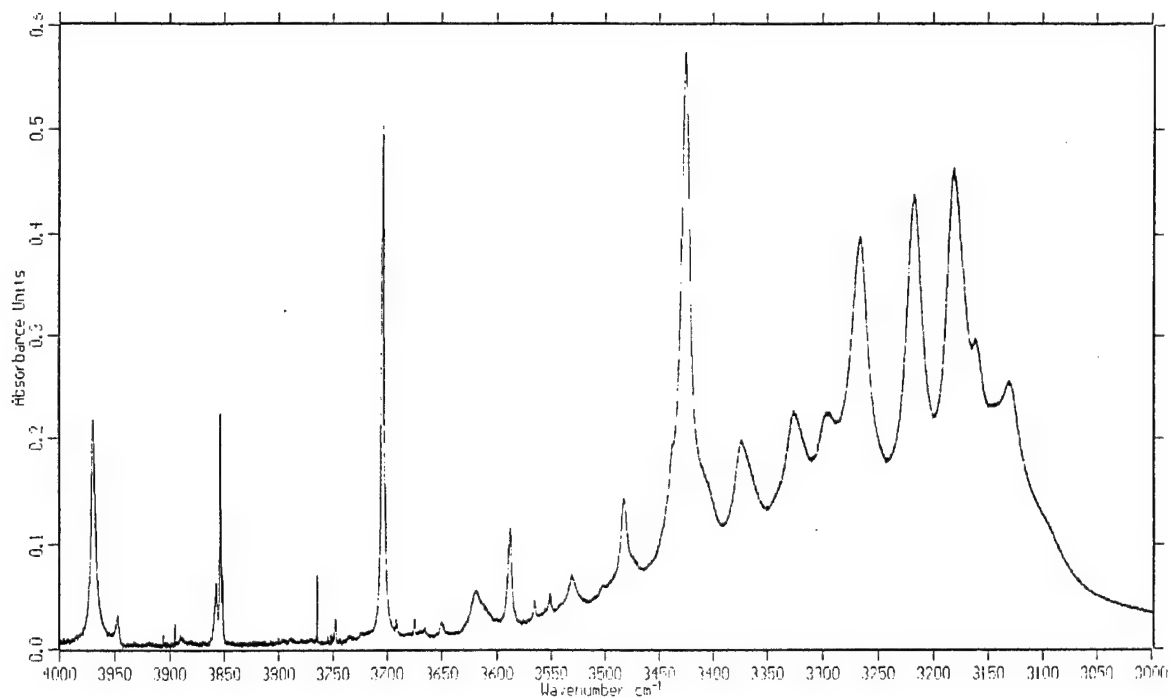
ppm
 123 PPM HF/pH₂ d≈3mm



st27115.15 annealed T=2.4K
 st27115.13 annealing T=4.8K
 st271215.9 as deposited T=2.4K

resolution = 0.005 cm⁻¹

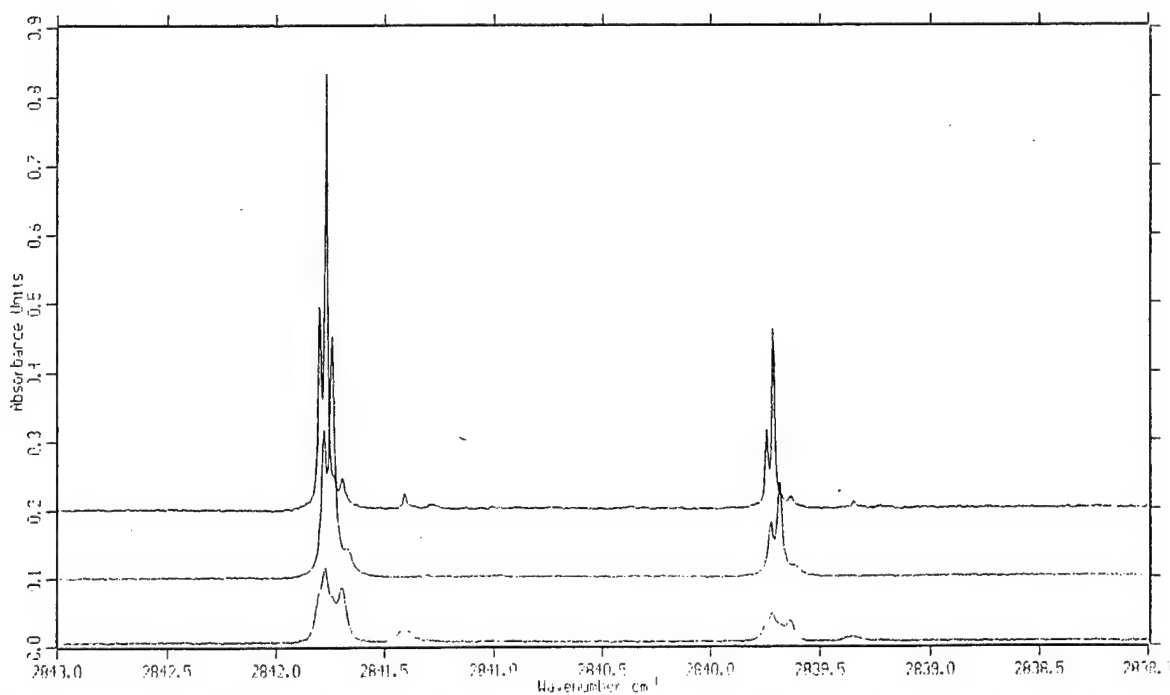
$(\text{HF})_n/\text{pH}_2$



st27133.15 sample burnoff T~10K 268 PPM HF/pH₂ resolution = 0.1 cm⁻¹

st27133.15

$\text{HF-HCl}/\text{pH}_2$



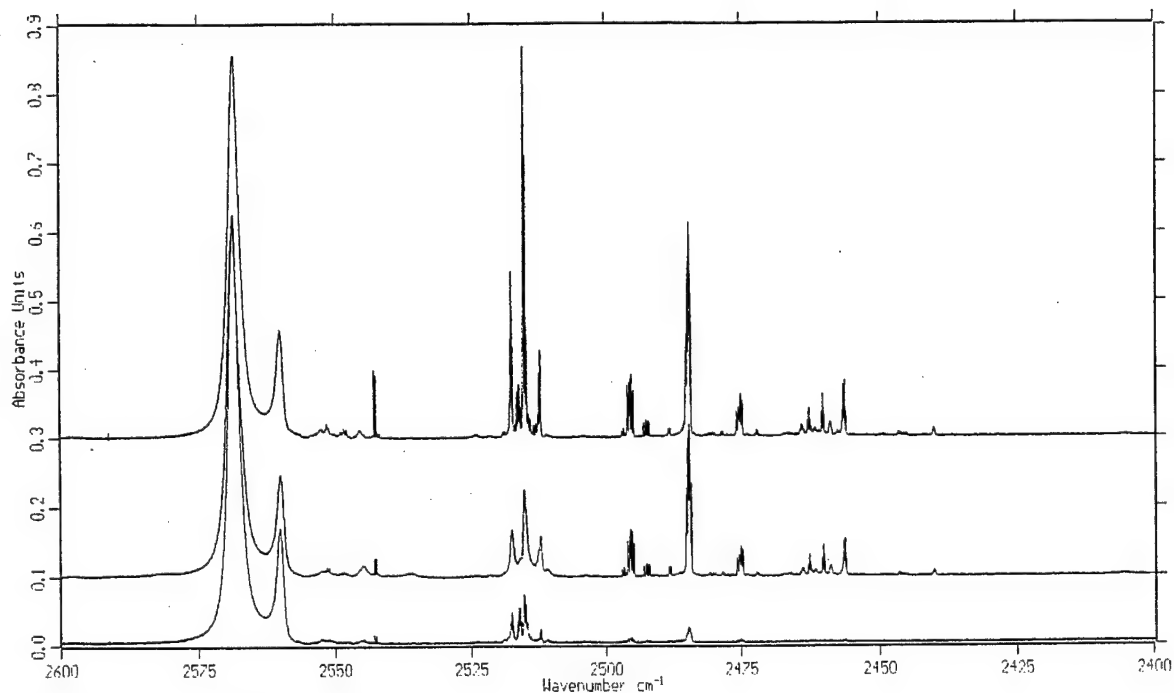
st27115.15 annealed T=2.4K
st27115.13 annealing T=4.8K
st27115.9 as deposited T=2.4K

123 PPM HF/pH₂ d≈3mm

resolution = 0.005 cm⁻¹

st27115.9

ppm
260 PPM HBr/pH₂ d≈3mm

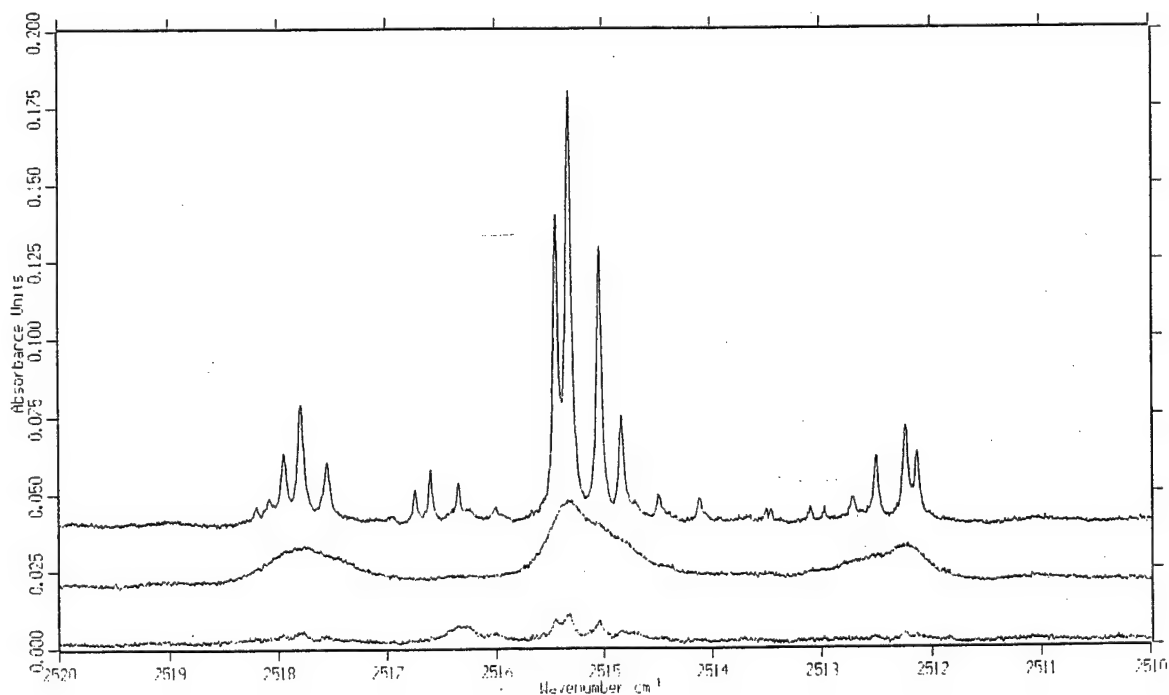


st27145.9 annealed T=2.4K
st27145.7 annealing T=4.8K
st27145.5 as deposited T=2.4K

resolution = 0.005 cm⁻¹

ST27145.5

(HBr)₂/pH₂



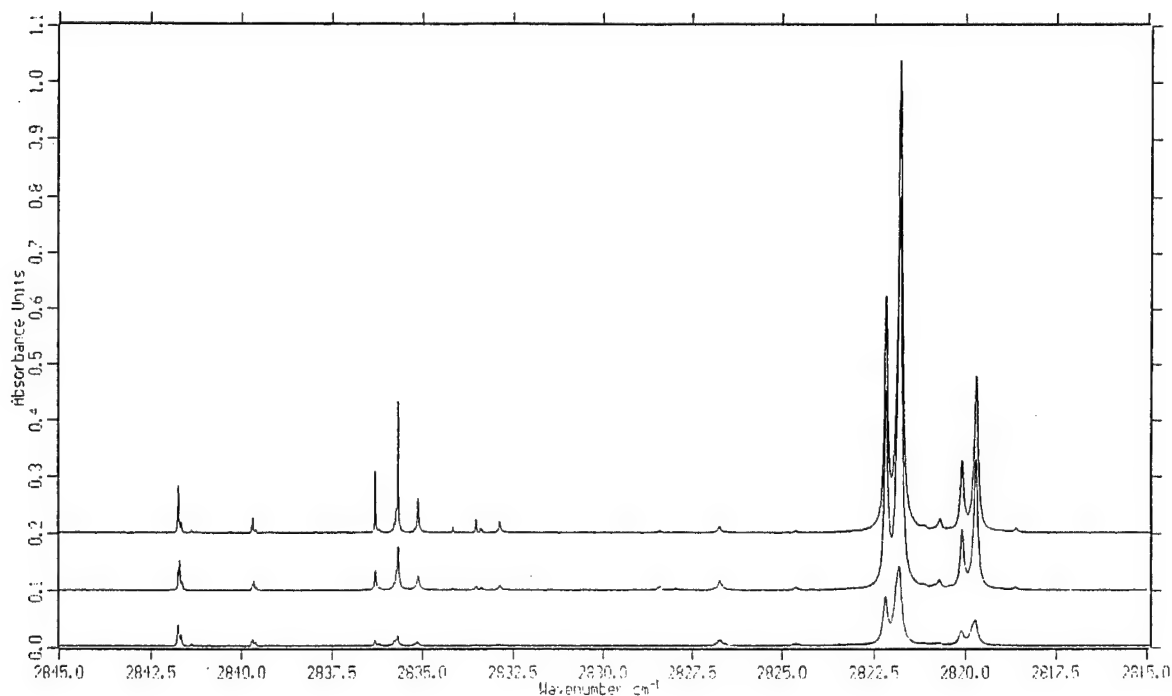
st27140.9 annealed T=2.4K
st27140.7 annealing T=4.8K
st27140.5 as deposited T=2.4K

80 PPM HBr/pH₂ d≈3mm

resolution = 0.005 cm⁻¹

ST27140.5

HCl-(HF, HCl, HBr)/pH₂

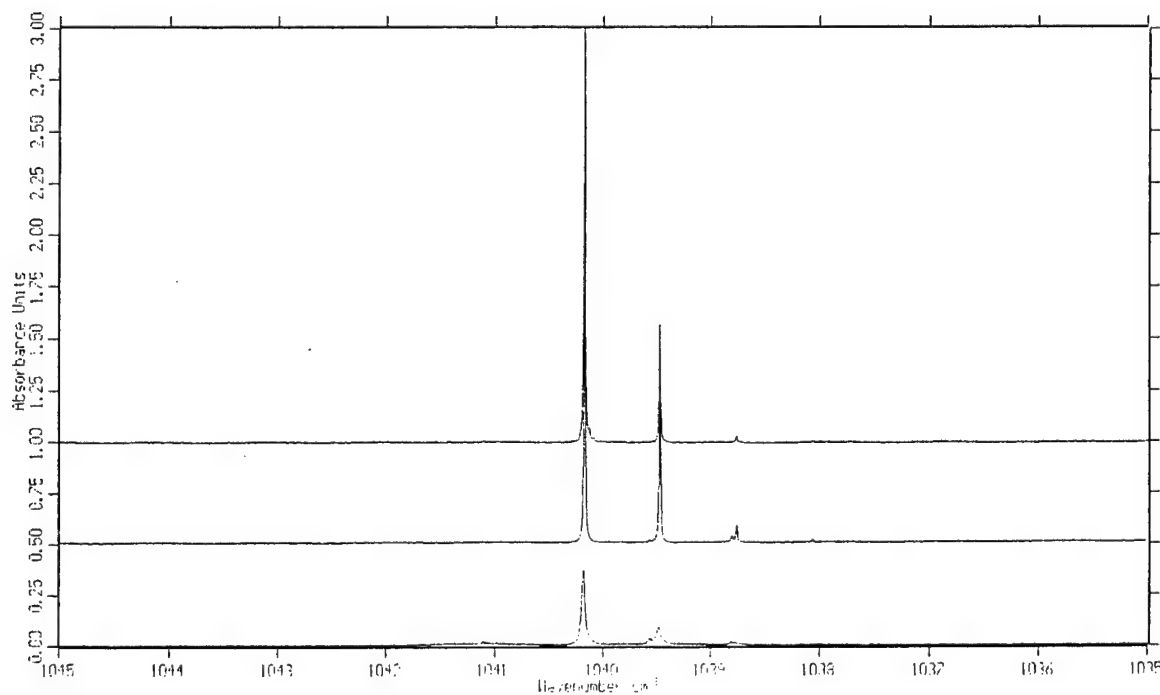


st27145.9 annealed T=2.4K
 st27145.7 annealing T=4.8K
 st27145.5 as deposited T=2.4K

260 PPM HBr/pH₂ d≈3mm

resolution = 0.005 cm⁻¹
 ST27145.5

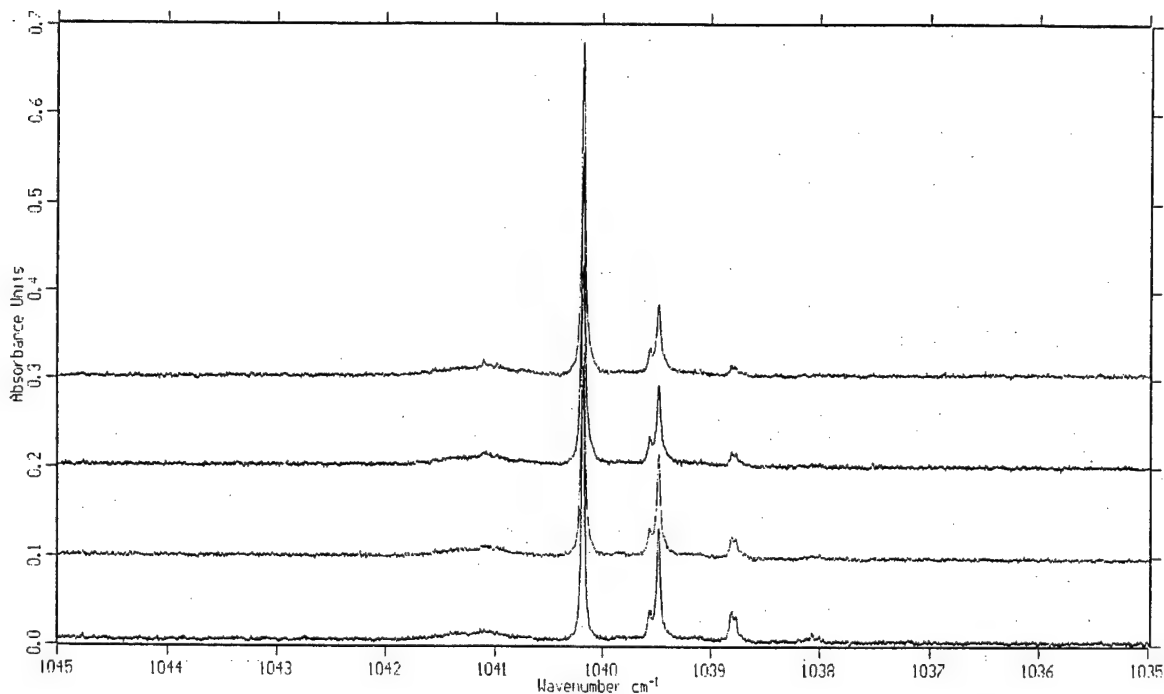
2.4 PPM CH₃F/pH₂ d≈3mm



st28060.15 annealed T=2.4K
 st28060.11 annealing T=4.8K
 st28060.6+7 as deposited T=2.4K

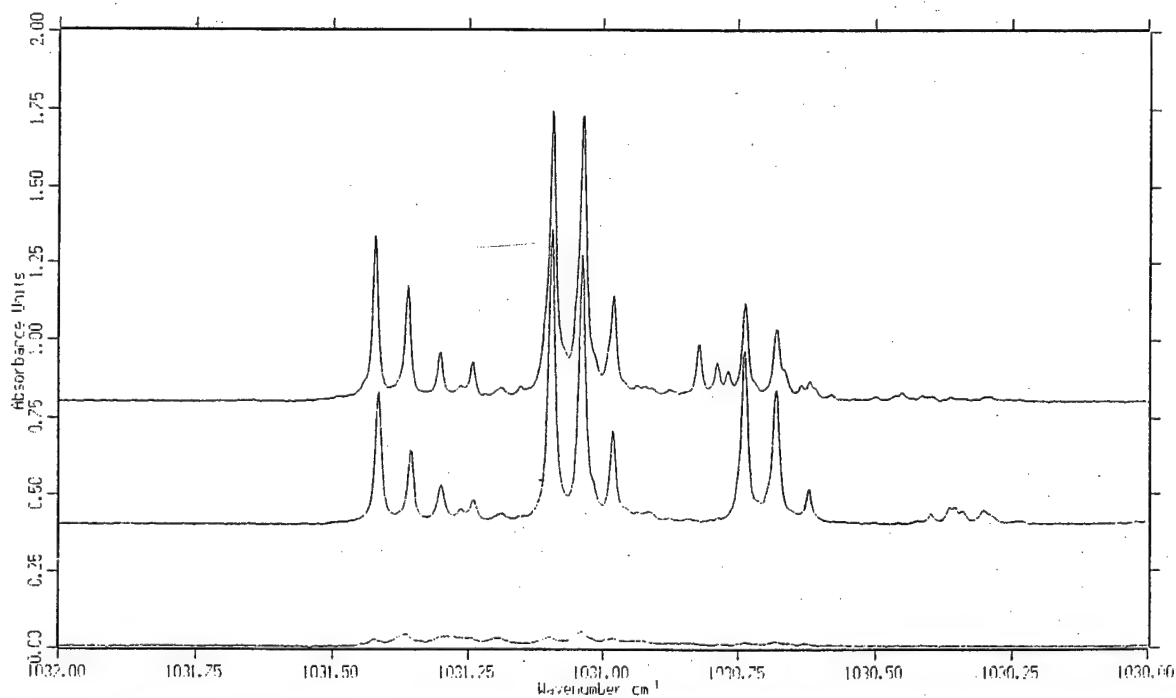
resolution = 0.005 cm⁻¹

^1H Spin Relaxation in $\text{CH}_3\text{F}/\text{pH}_2$



st28060.7 after 100 min T=2.4K
 st28060.6 after 70 min T=2.4K
 st28060.3 after 30 min T=2.4K
 st28060.2 as deposited T=2.4K
 resolution = 0.005 cm^{-1}
 ST28060.2

$(\text{CH}_3\text{F})_2/\text{pH}_2$



st28044.11 annealed T=2.4K
 st28044.7 annealing T=4.8K
 st28044.3 as deposited T=2.4K
 30 PPM $\text{CH}_3\text{F}/\text{pH}_2$
 resolution = 0.005 cm^{-1}

ST28044.7

SUPPLEMENTAL MATERIALS

for the poster:

HIGH ENERGY DENSITY MATTER CONTRACTORS CONFERENCE
Cocoa Beach, FL 8-11 June 1999

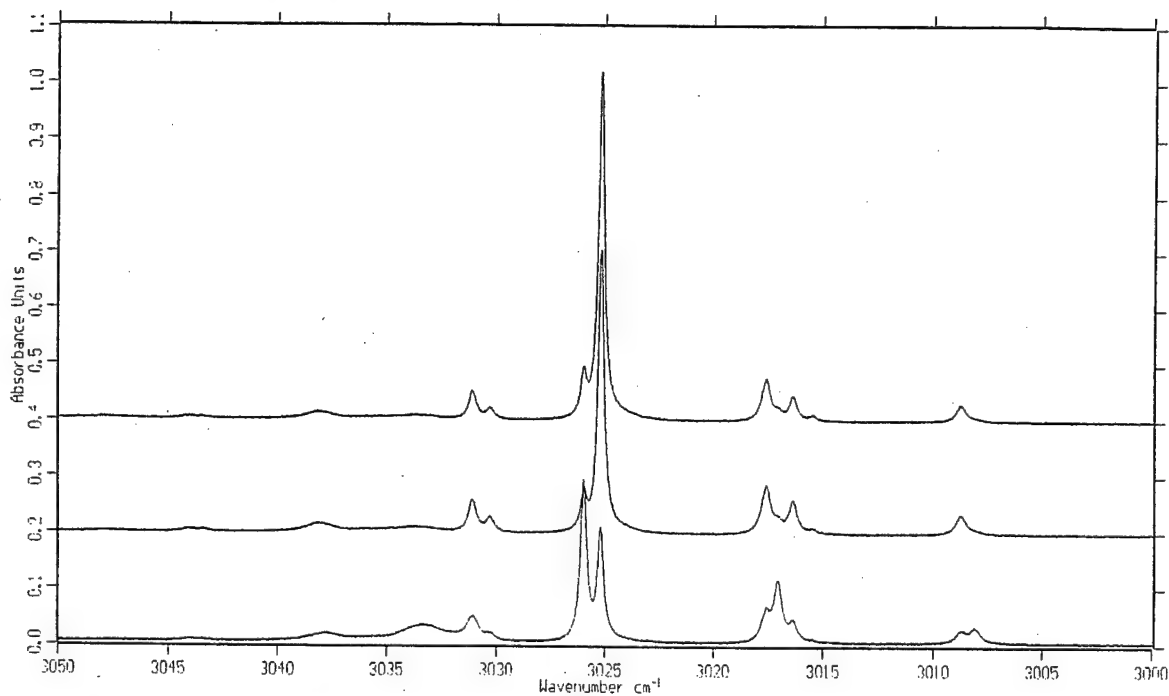
High Resolution Infrared Absorption Spectroscopy of Molecular Dopants in Cryogenic Solid Parahydrogen

Mario E. Fajardo and Simon Tam

US Air Force Research Laboratory, Propulsion Directorate
(AFRL/PRSP Bldg. 8451, Edwards AFB, CA 93524-7680) mario_fajardo@ple.af.mil

Consisting of spectra of NON-ENERGETIC species trapped in solid hydrogen at low concentrations. These data encompass prototypical diatomic (CO, HCl, HF, HBr), triatomic (CO₂, N₂O, H₂O), linear polyatomic (C₂H₂), symmetric top (NH₃, CH₃F), and spherical top (CH₄) molecular dopants. The basic research activity of understanding these spectra will aid in the future characterization of HEDM cryosolid propellants.

ppm
13 PPM CH₄/pH₂ d≈3mm



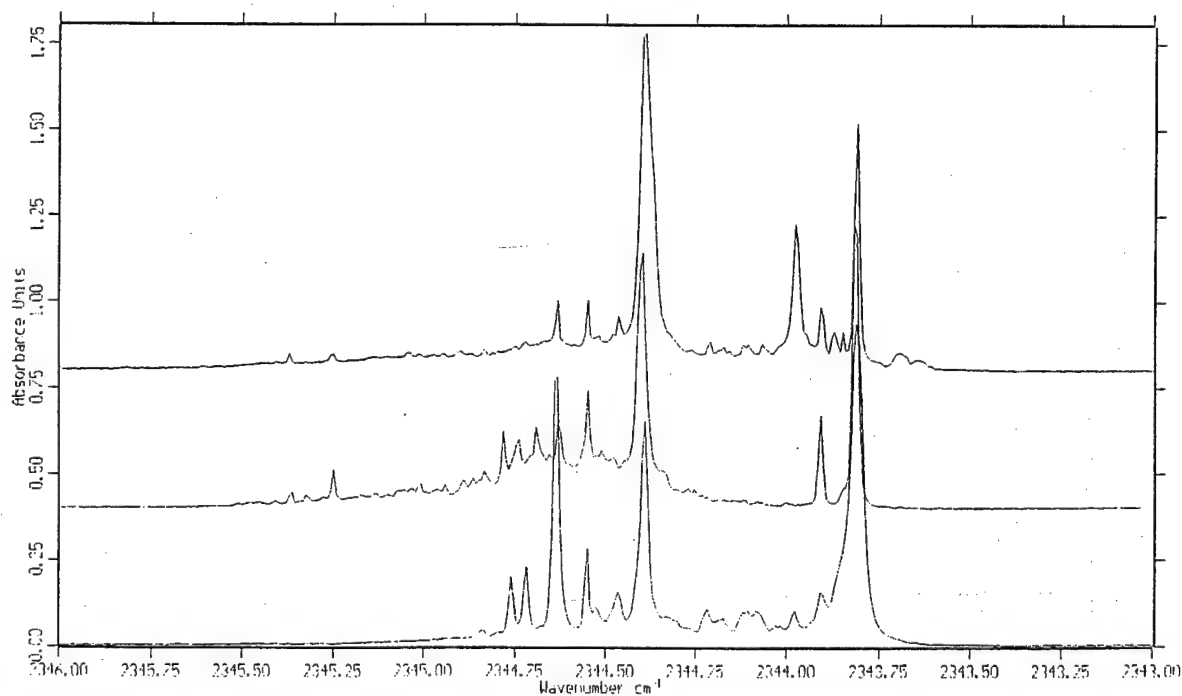
st27011.8
st27011.4
st27011.2

annealed T=2.4K
annealing T=4.8K
as deposited T=2.4K

resolution = 0.0075 cm⁻¹

ST27011.2

ppm
1 PPM CO₂/pH₂ d≈3mm



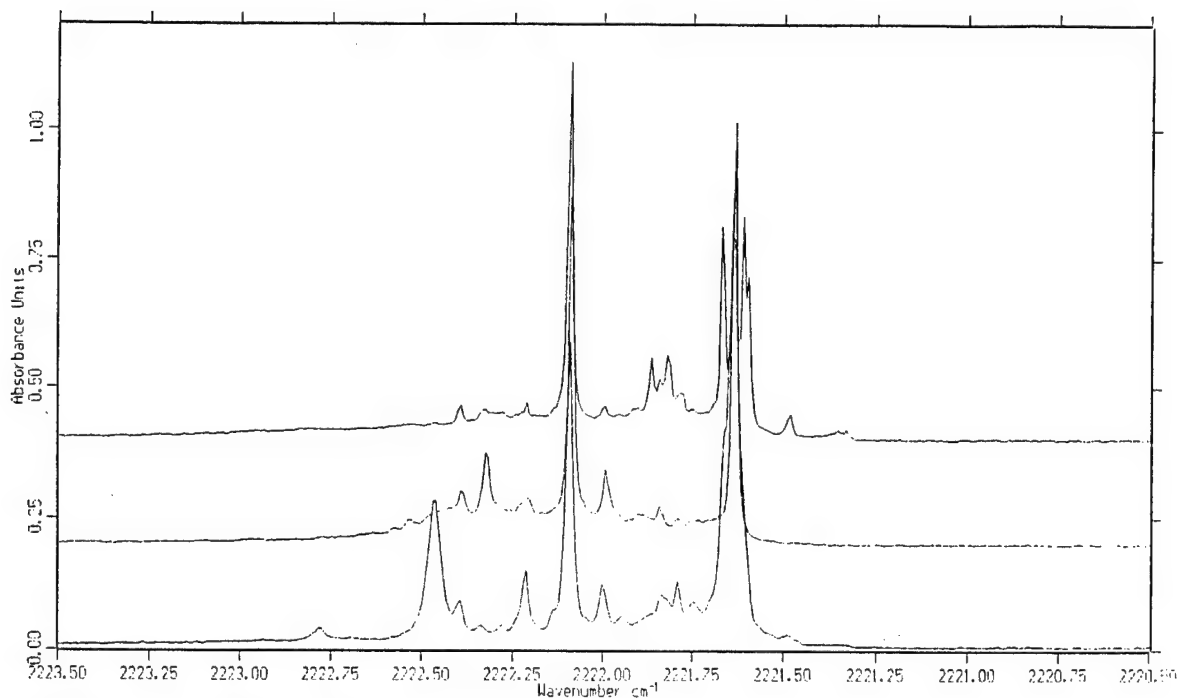
st27025.11
st27025.9
st27025.7

annealed T=2.4K
annealing T=4.8K
as deposited T=2.4K

resolution = 0.005 cm⁻¹

ST27025.7

ppm
1 PPM $\text{N}_2\text{O}/\text{pH}_2$ $d \approx 3\text{mm}$

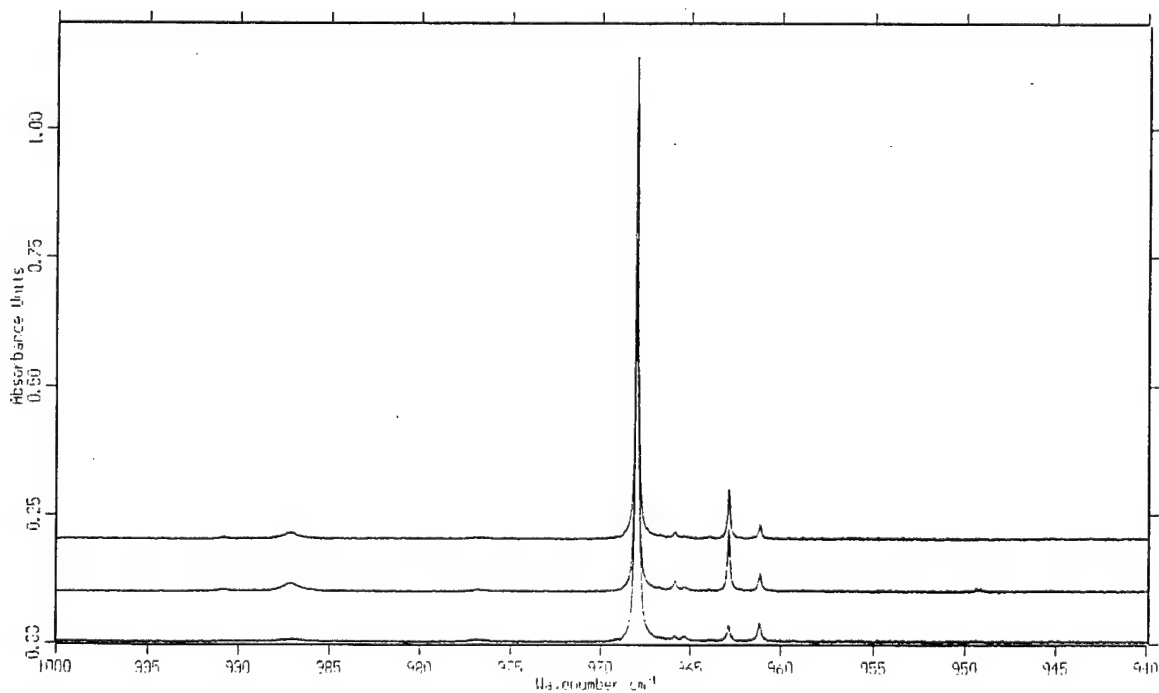


st27025.14 annealed T=2.4K
st27025.12 annealing T=4.8K
st27025.6 as deposited T=2.4K
31

resolution = 0.005 cm^{-1}

ST27031.6

ppm
4 PPM NH_3/pH_2 $d \approx 3\text{mm}$

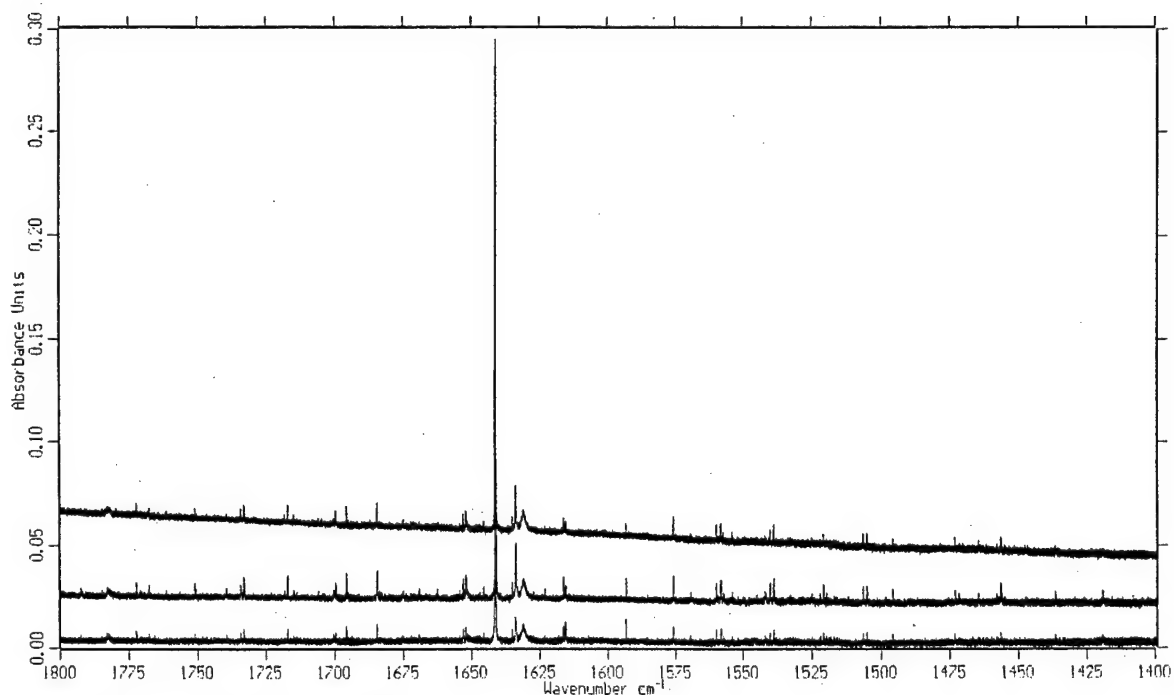


st27036.12 annealed T=2.4K
st27036.10 annealing T=4.8K
st27036.8 as deposited T=2.4K

resolution = 0.005 cm^{-1}

ST27039.6

ppm
4 PPM NH_3/pH_2 $d \approx 3\text{mm}$

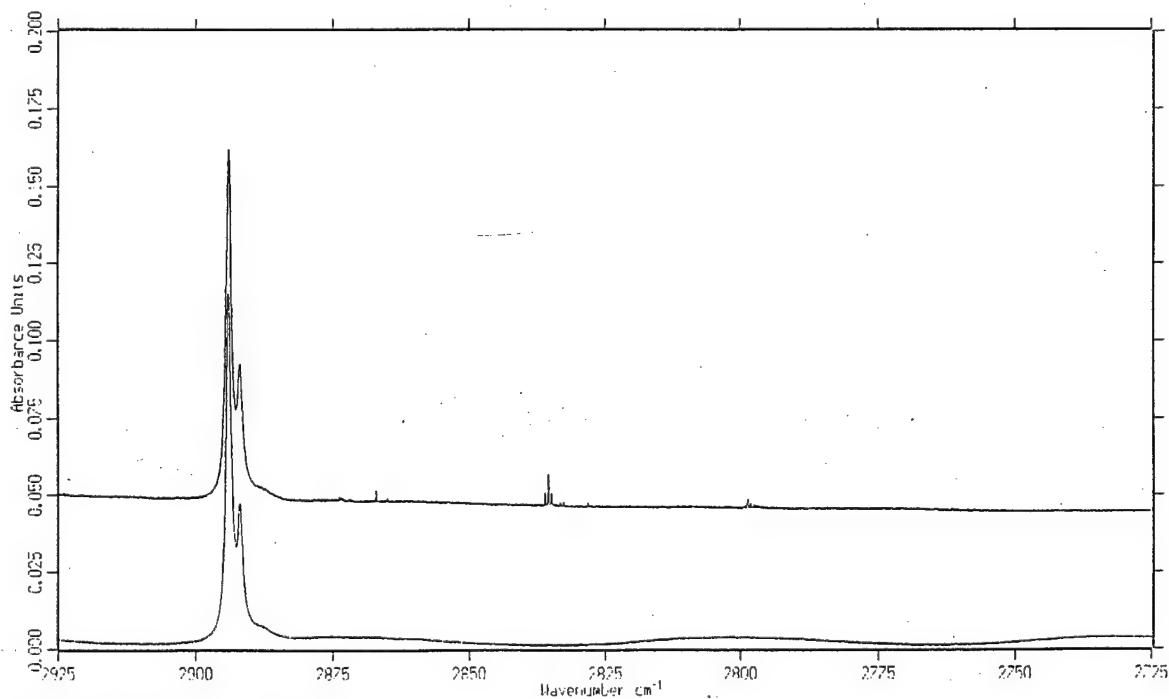


st27036.12 annealed T=2.4K
st27036.10 annealing T=4.8K
st27036.8 as deposited T=2.4K

resolution = 0.005 cm^{-1}

ST27036.8

ppm
8 PPM HCl/pH_2 $d \approx 3\text{mm}$

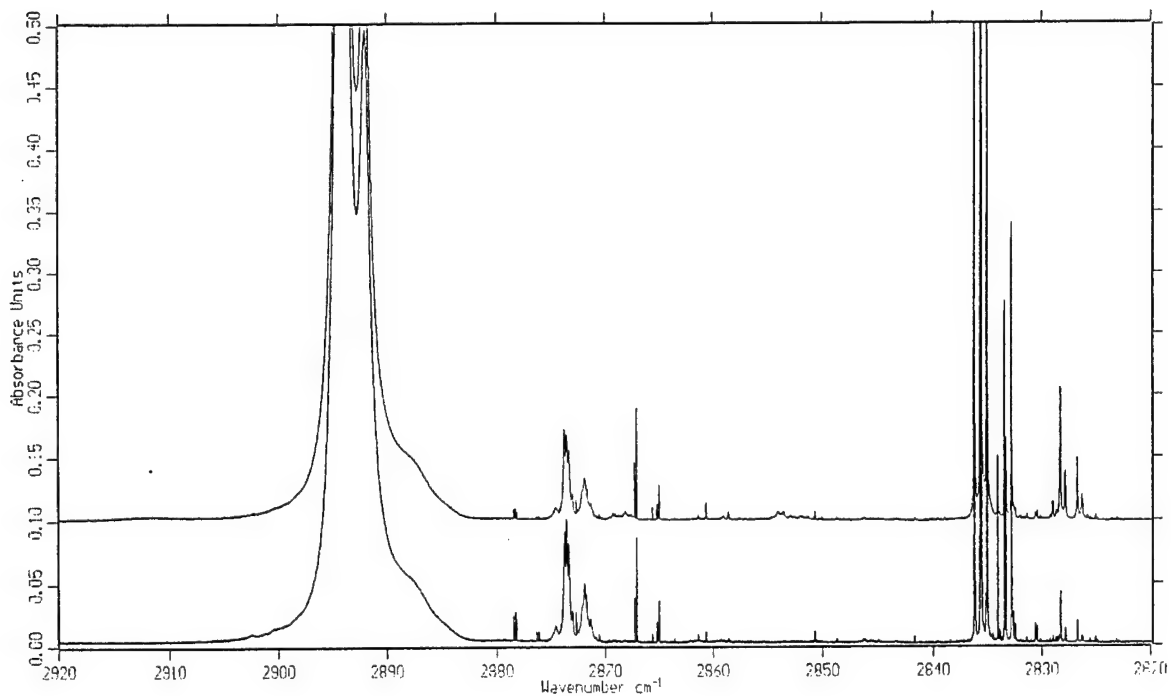


st27055.11 annealed T=2.4K
st27055.4 as deposited T=2.4K
resolution = 0.05 cm^{-1}

ST27055.4

ST27055.4

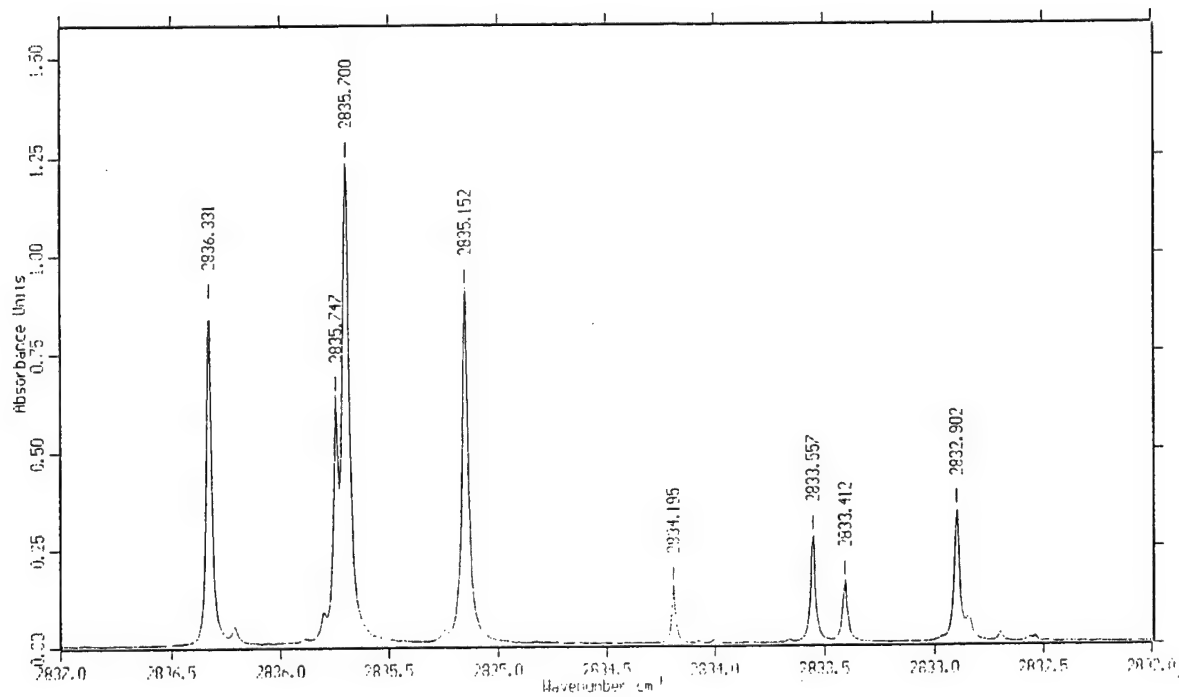
reversible T dependences



88 PPM HCl
st27061.9 annealing T=4.8K
st27061.11 annealed T=2.4K

st27061.9

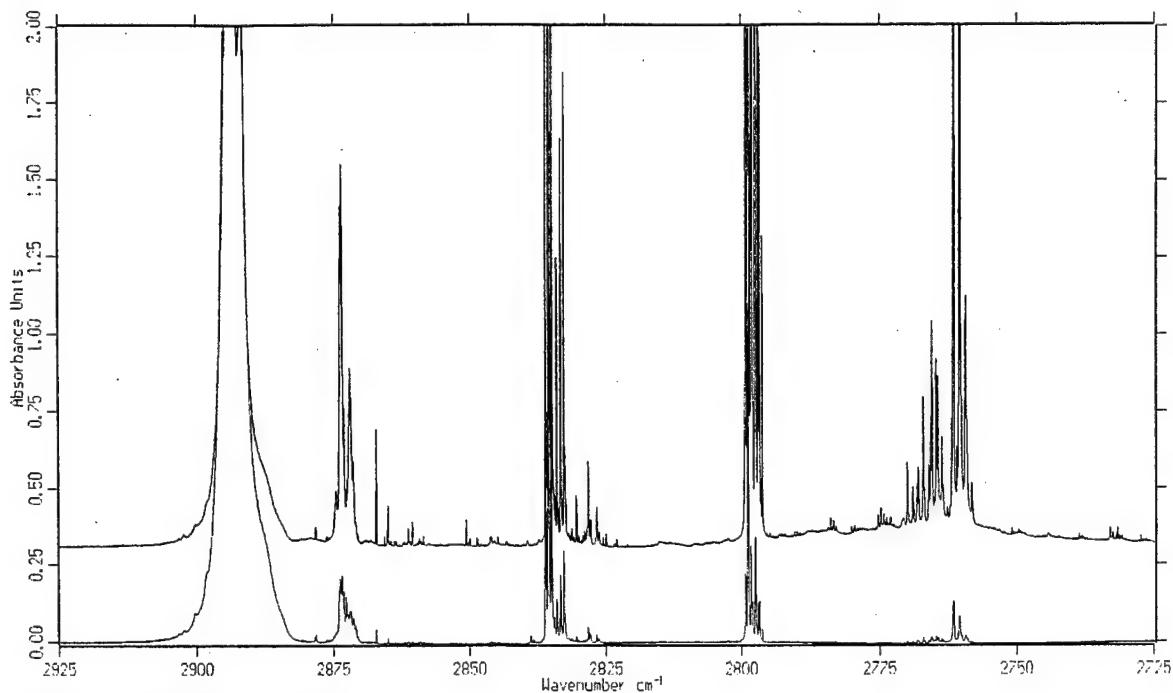
$(\text{HCl})_2 \nu_2^+$ region



st27061.11 annealed T=2.4K 88 PPM HCl

st27061.11

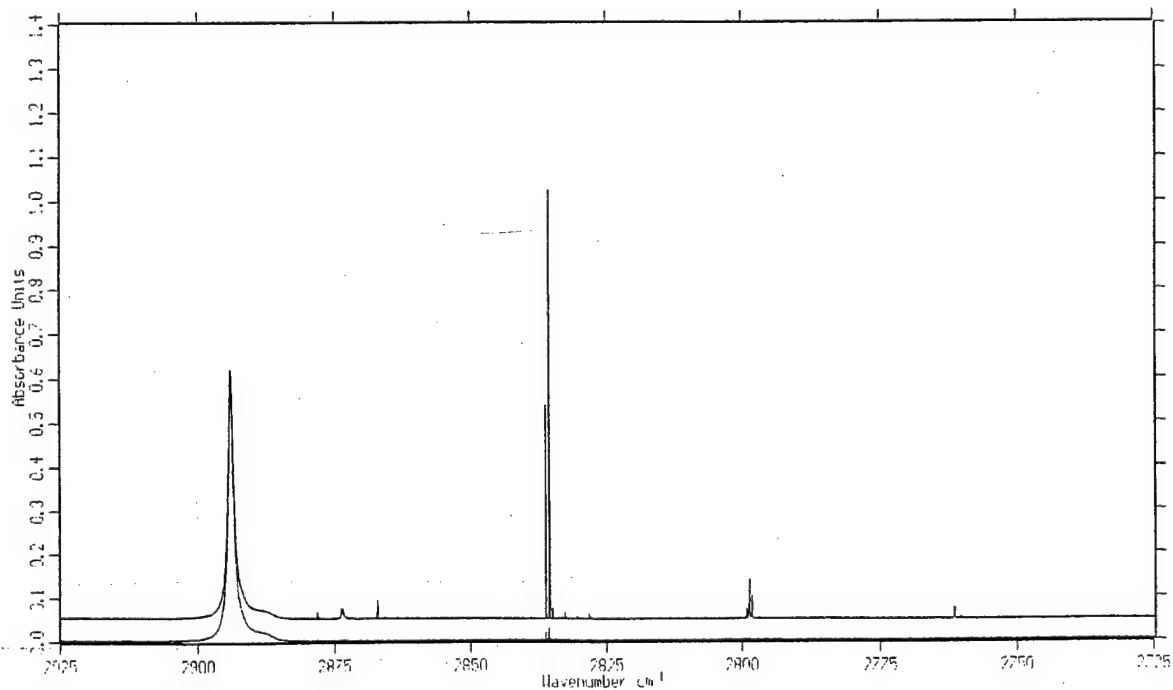
ppm
494 PPM HCl/pH₂ d≈3mm



st27067.10 annealed T=2.4K
st27067.6 as deposited T=2.4K
resolution = 0.0075 cm⁻¹

st27067.6

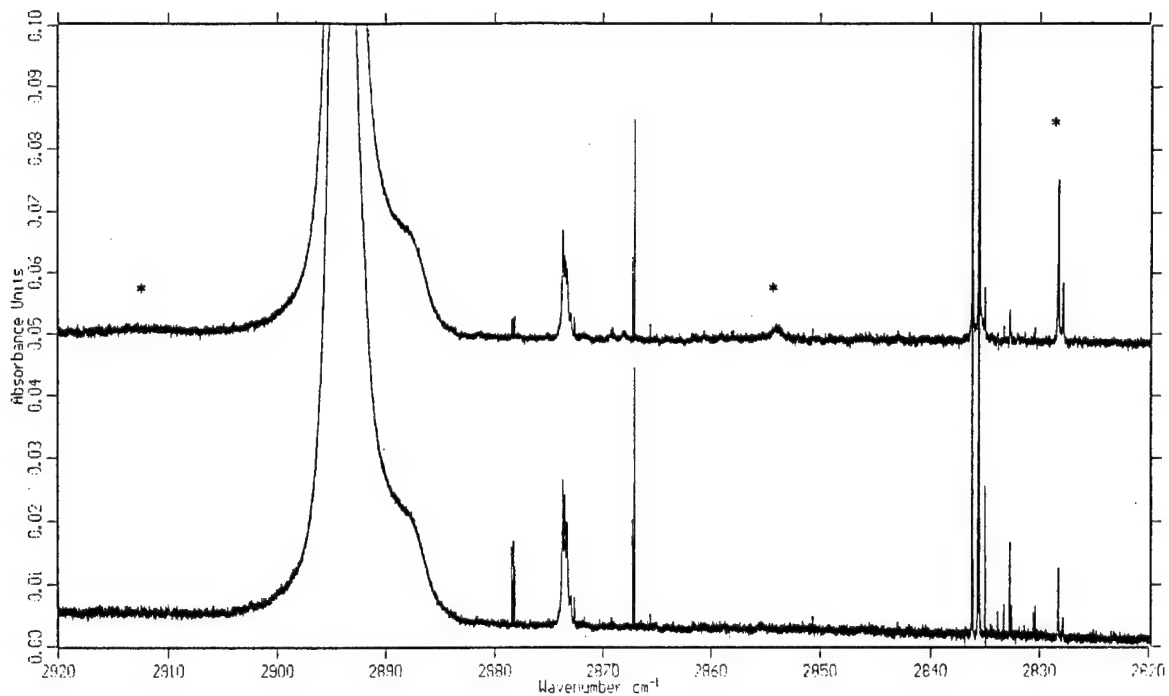
ppm
30 PPM H³⁵Cl/pH₂ d≈3mm



st27073.17 annealed T=2.4K
st27073.9 as deposited T=2.4K
resolution = 0.005 cm⁻¹

st27073.9

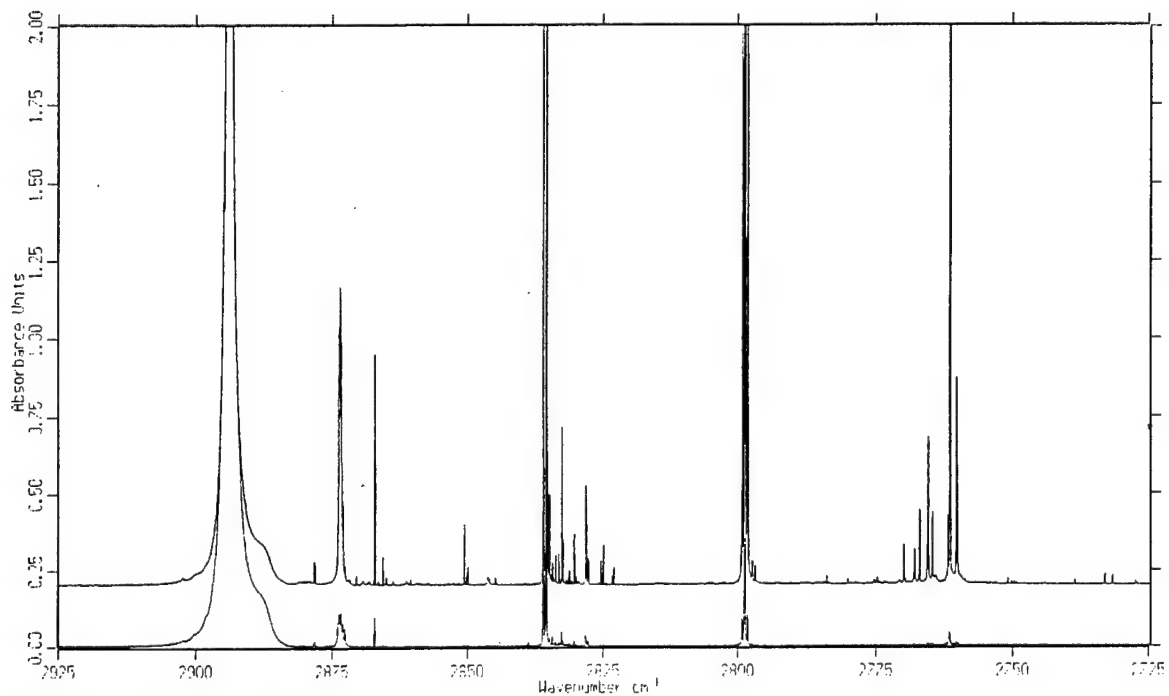
reversible T dependences



30 PPM H^{35}Cl
 st27073.11 annealing T=4.8K
 st27073.17 annealed T=2.4K

ST27073.11

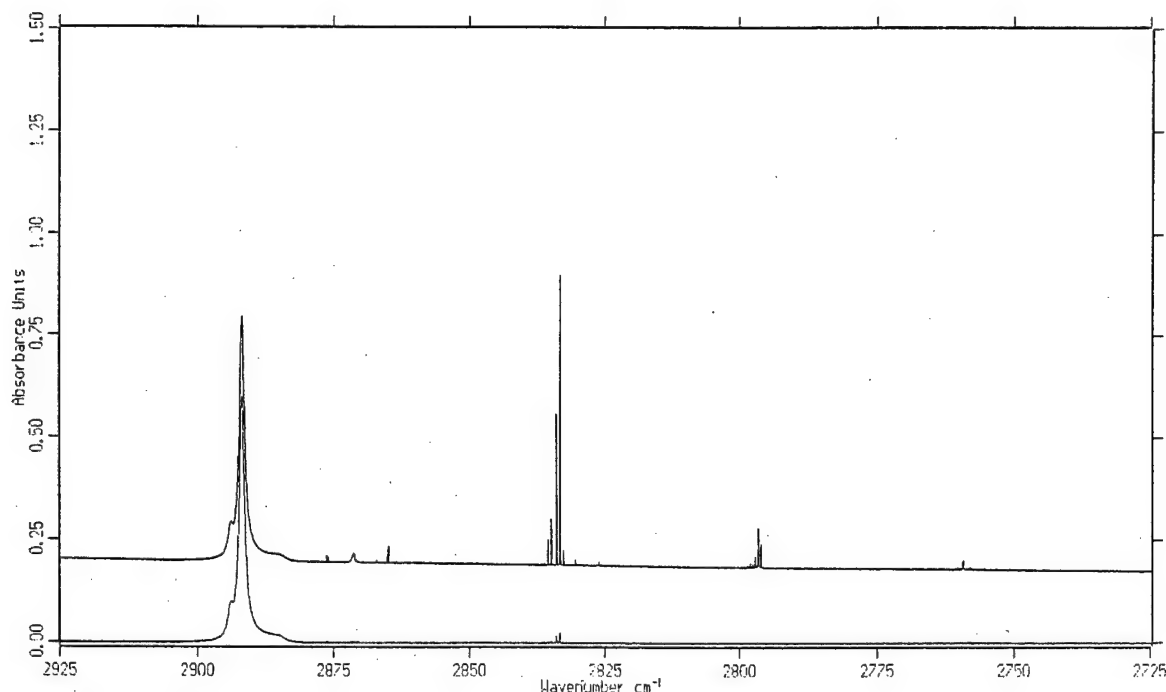
284 ^{ppm} $\text{H}^{35}\text{Cl}/\text{pH}_2$ $d \approx 3\text{mm}$



st27085.9 annealed T=2.4K
 st27085.5 as deposited T=2.4K
 resolution = 0.005 cm^{-1}

ST27085.9

33 ^{ppm} PPM H³⁷Cl/pH₂ d≈3mm



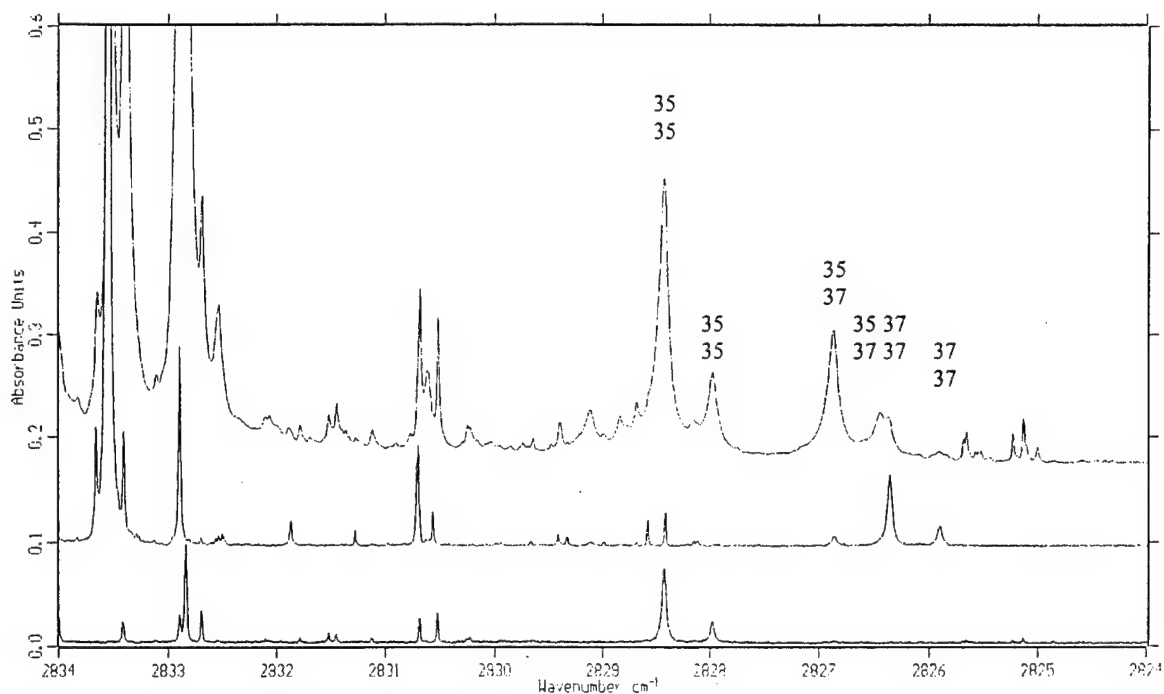
st27097.6 annealed T=2.4K
st27097.2 as deposited T=2.4K
resolution = 0.005 cm⁻¹

ST27097.2

HCl monomer shifts

<u>species</u>	<u>line/band</u>	<u>gas phase (cm⁻¹)</u>	<u>solid pH₂</u>	<u>gas-matrix</u>
H ³⁵ Cl	R(1)	2925.8961	2912	14
	R(0)	2906.2464	2894.2	12.1
	"Q(0)"	2885.67	2873.86	
			2873.67	12.0
			2873.46	
			2873.14	
	P(1)	2865.0977	2854.12	
			2853.58	11.5
			2852.95	
H ³⁷ Cl	R(1)	2923.7315	2910.2	13.5
	R(0)	2904.1104	2892.1	12.0
	"Q(0)"	2883.57	2871.69	
			2871.48	12.1
			2871.31	
			2870.97	
	P(1)	2863.0231	2852.07	
			2851.55	11.5
			2850.89	

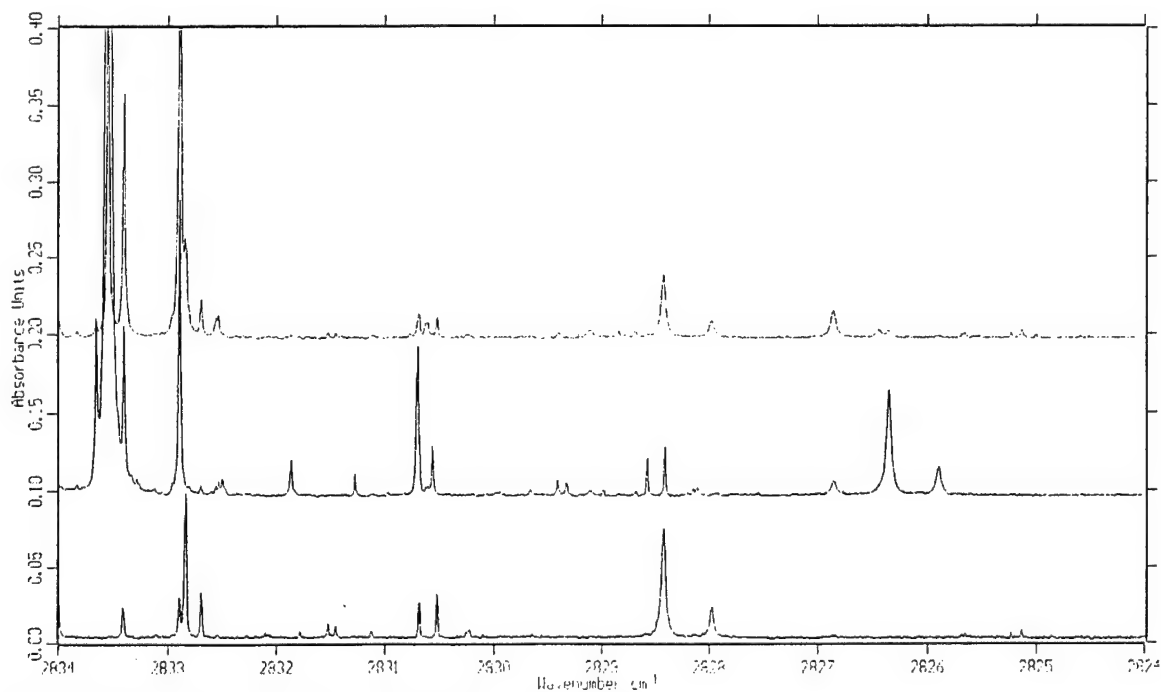
$(\text{HCl})_2$ ν_2^- region



st27067.10 annealed T=2.4K 494 PPM HCl
 st27103.6 annealed T=2.4K 94 PPM H^{37}Cl
 st27079.11 annealed T=2.4K 90 PPM H^{35}Cl

st27067.10

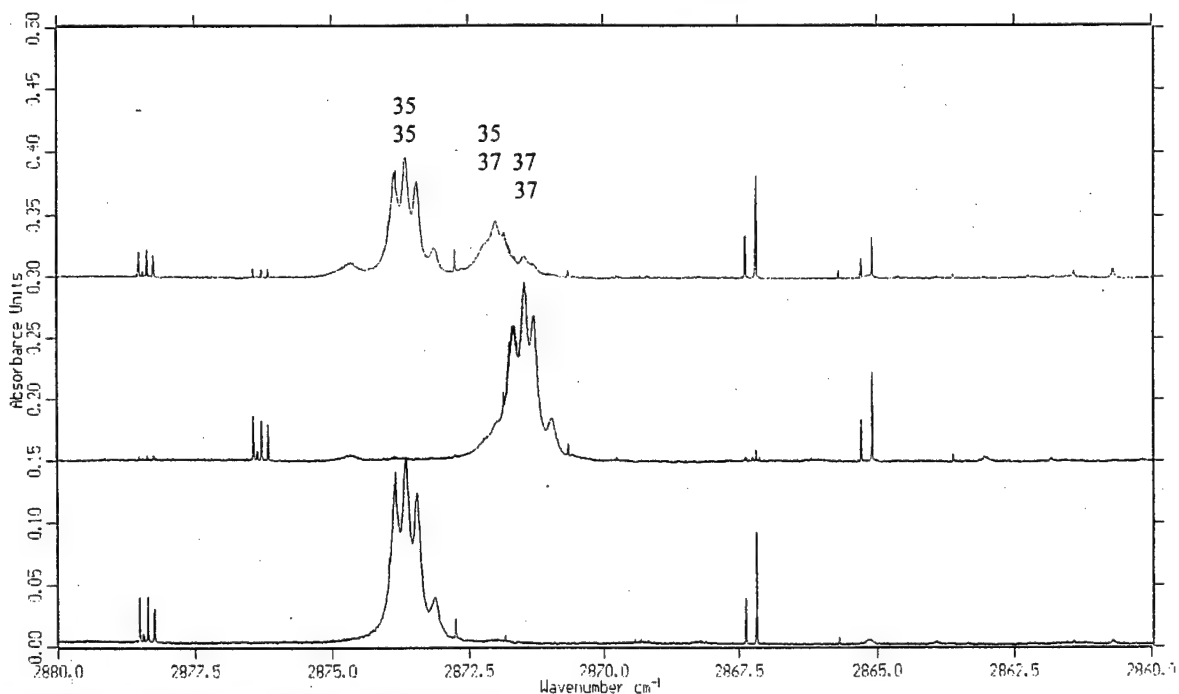
$(\text{HCl})_2$ ν_2^- region



st27061.11 annealed T=2.4K 88 PPM HCl
 st27103.6 annealed T=2.4K 94 PPM H^{37}Cl
 st27079.11 annealed T=2.4K 90 PPM H^{35}Cl

st27061.11

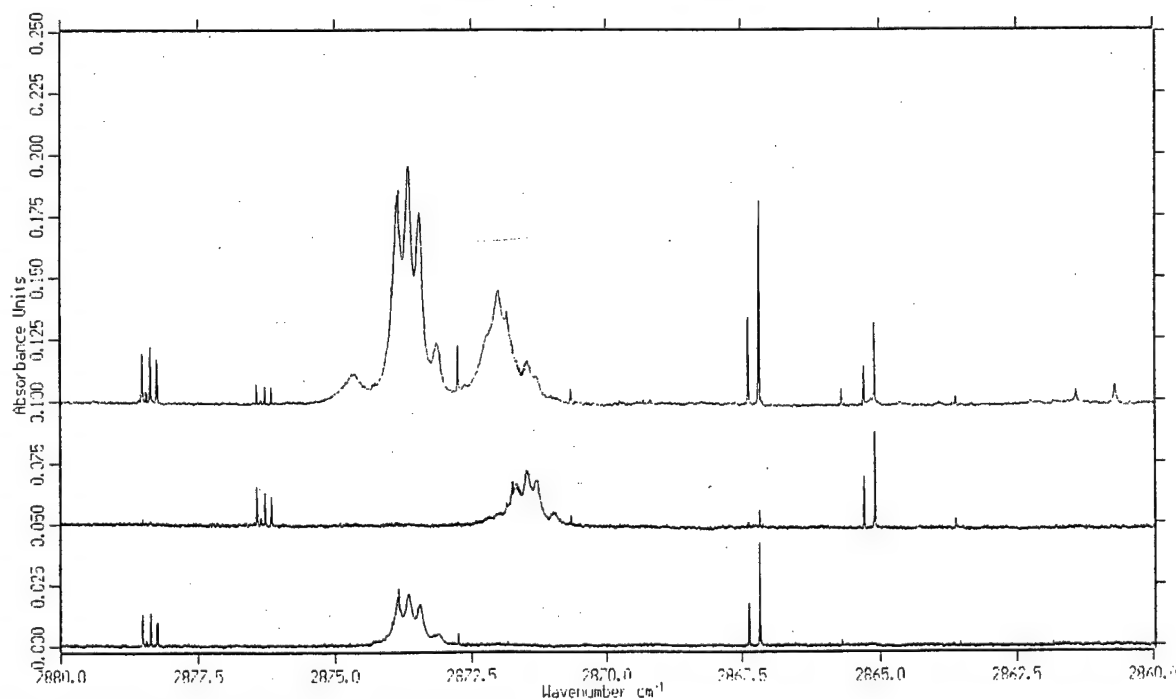
$(\text{HCl})_2 \nu_1^+$ region



st27061.11 annealed T=2.4K 88 PPM HCl
 st27103.6 annealed T=2.4K 94 PPM H³⁷Cl
 st27079.11 annealed T=2.4K 90 PPM H³⁵Cl

ST27103.6

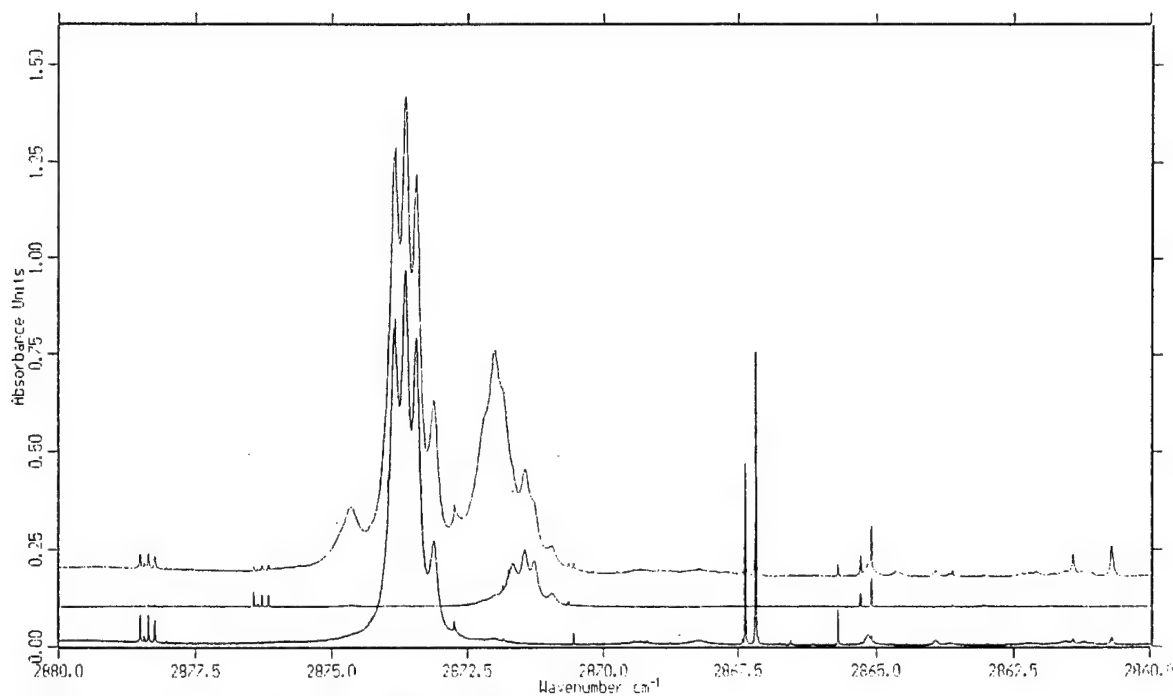
$(\text{HCl})_2 \nu_1^+$ region



st27061.11 annealed T=2.4K 88 PPM HCl
 st27097.6 annealed T=2.4K 33 PPM H³⁷Cl
 st27073.17 annealed T=2.4K 30 PPM H³⁵Cl

ST27073.17

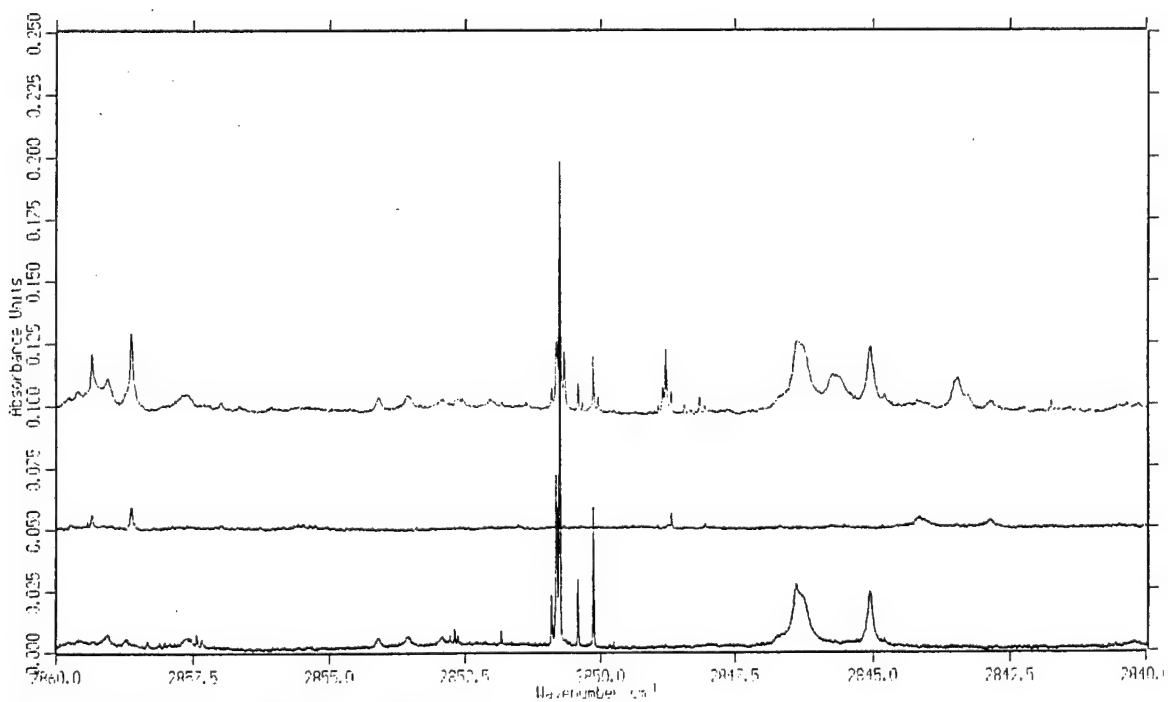
$(\text{HCl})_2 \nu_1^+$ region



st27067.10	annealed	T=2.4K	494 PPM HCl
st27103.6	annealed	T=2.4K	94 PPM H^{37}Cl
st27085.9	annealed	T=2.4K	284 PPM H^{35}Cl

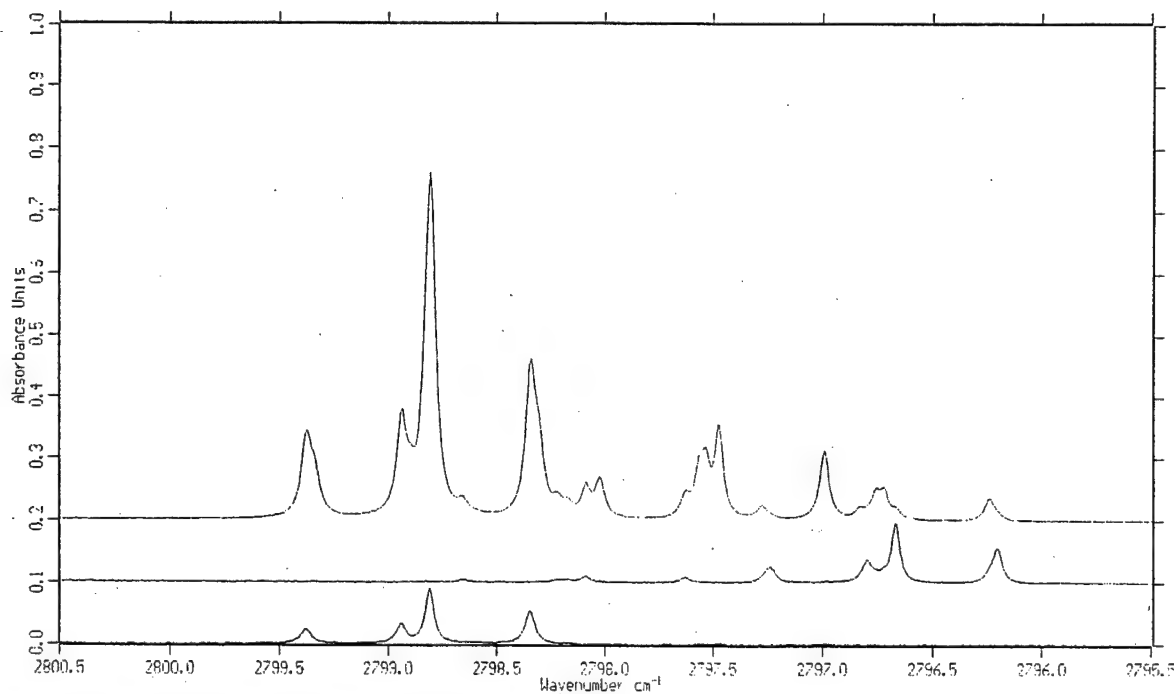
st27103.6

$(\text{HCl})_n$



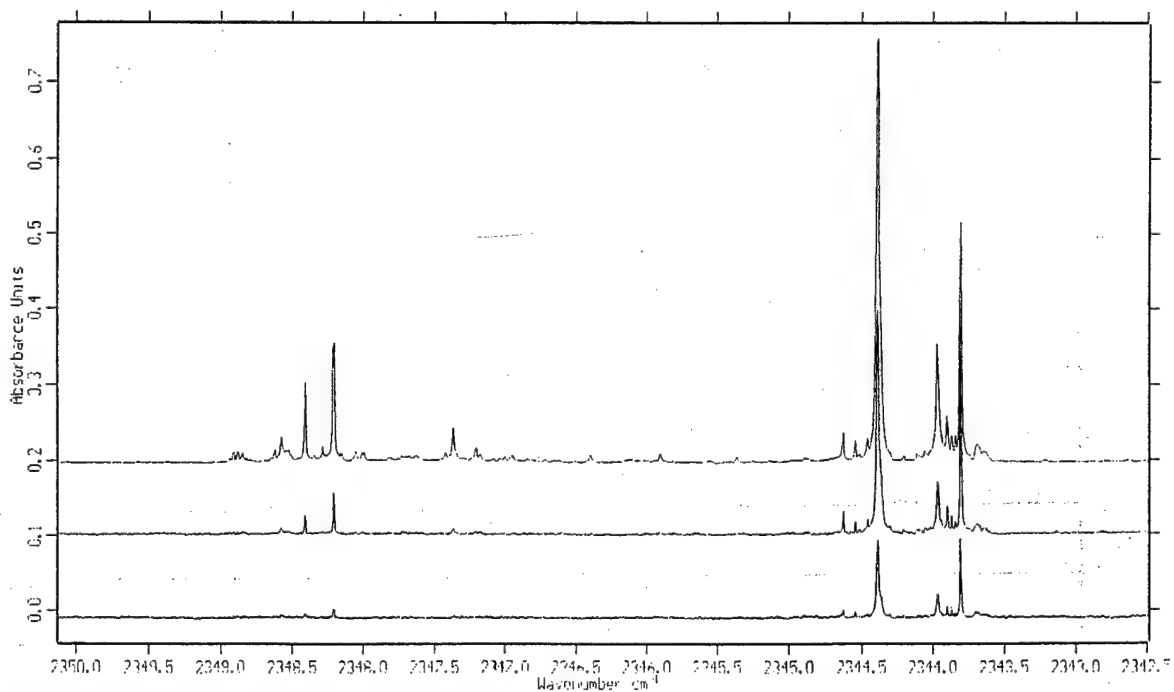
st27067.10	annealed	T=2.4K	494 PPM HCl
st27103.6	annealed	T=2.4K	94 PPM H^{37}Cl
st27085.9	annealed	T=2.4K	284 PPM H^{35}Cl

st27103.6



st27061.11	annealed	T=2.4K	88 PPM HCl
st27097.6	annealed	T=2.4K	33 PPM H^{37}Cl
st27073.17	annealed	T=2.4K	30 PPM H^{35}Cl

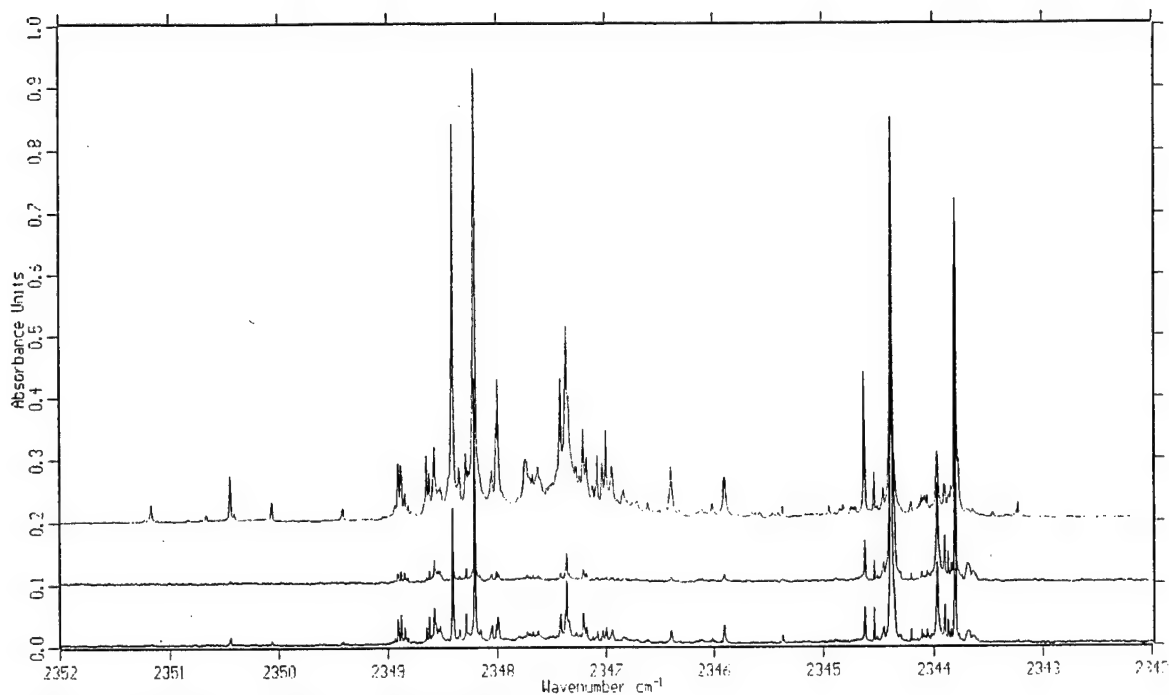
st27061.11



st27061.11	annealed	T=2.4K	88 PPM HCl
st27097.6	annealed	T=2.4K	33 PPM H^{37}Cl
st27073.17	annealed	T=2.4K	30 PPM H^{35}Cl

st27061.11

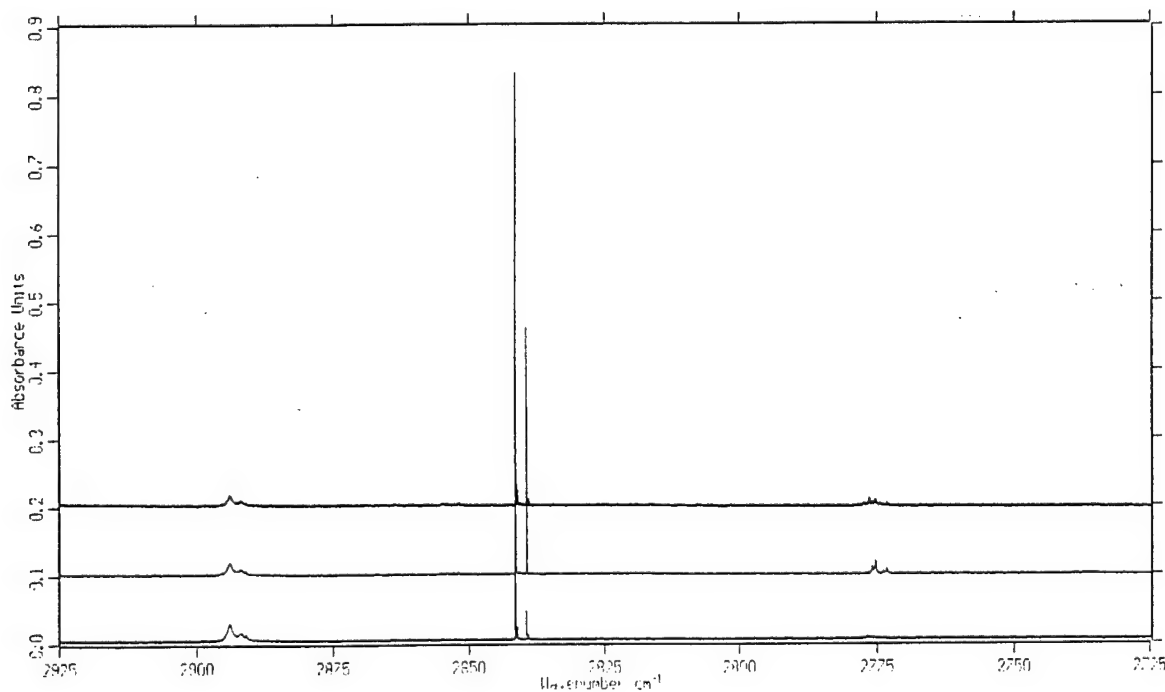
v_3 CO₂/(HCl)_n clusters



st27067.10 annealed T=2.4K 494 PPM HCl
 st27103.6 annealed T=2.4K 94 PPM H³⁷Cl
 st27085.9 annealed T=2.4K 284 PPM H³⁵Cl

st27103.6

HF-HCl/pH₂



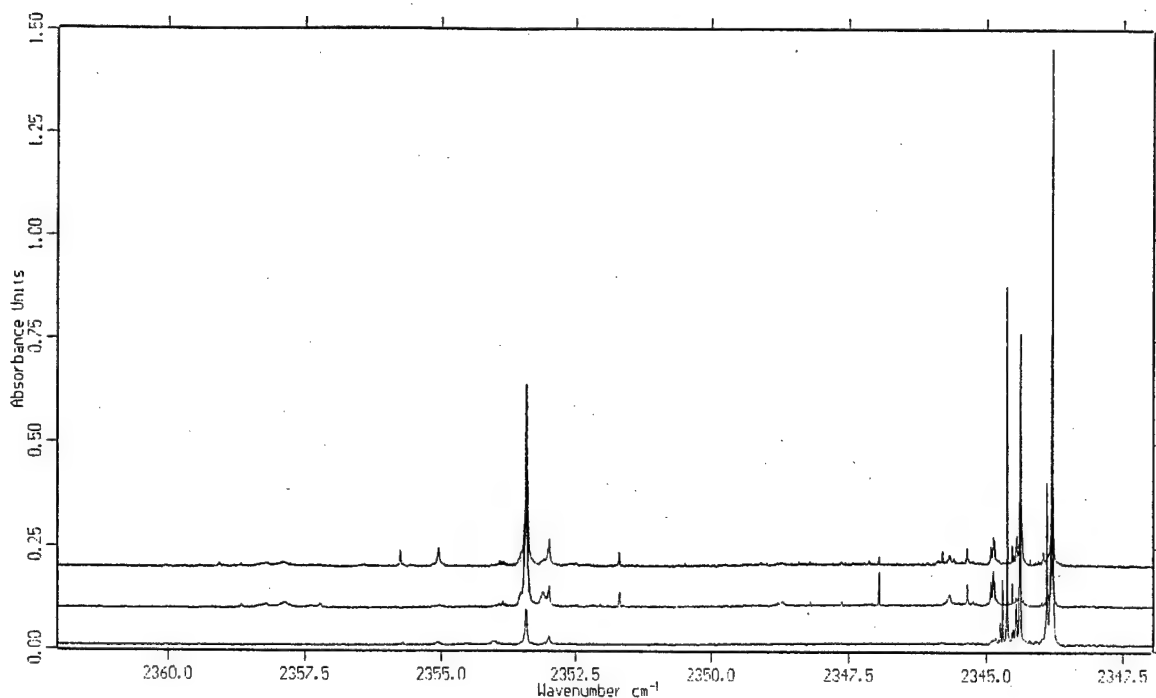
st27115.15 annealed T=2.4K
 st27115.13 annealing T=4.8K
 st27115.9 as deposited T=2.4K

123 PPM HF/pH₂ d≈3mm

resolution = 0.005 cm⁻¹

st27115.9

CO₂-HF/pH₂



st27115.15
st27115.13
st27115.9

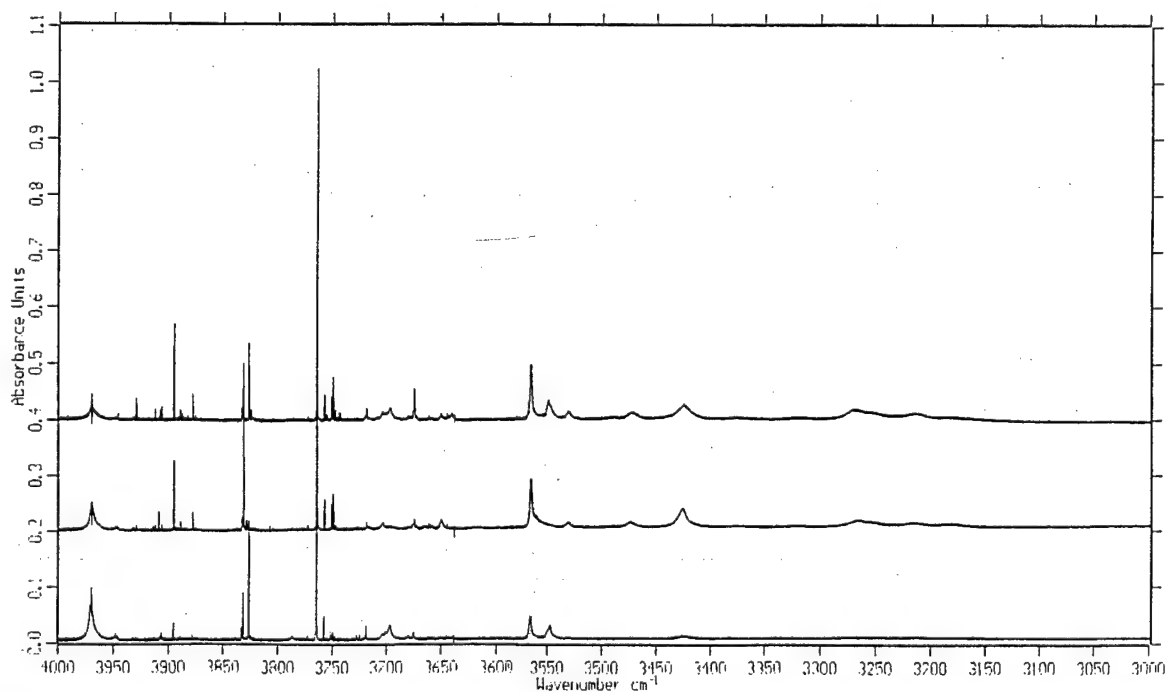
annealed T=2.4K
annealing T=4.8K
as deposited T=2.4K

123 PPM HF/pH₂ d≈3mm

resolution = 0.005 cm⁻¹

ST27115.9

27 PPM HF/pH₂ d≈3mm



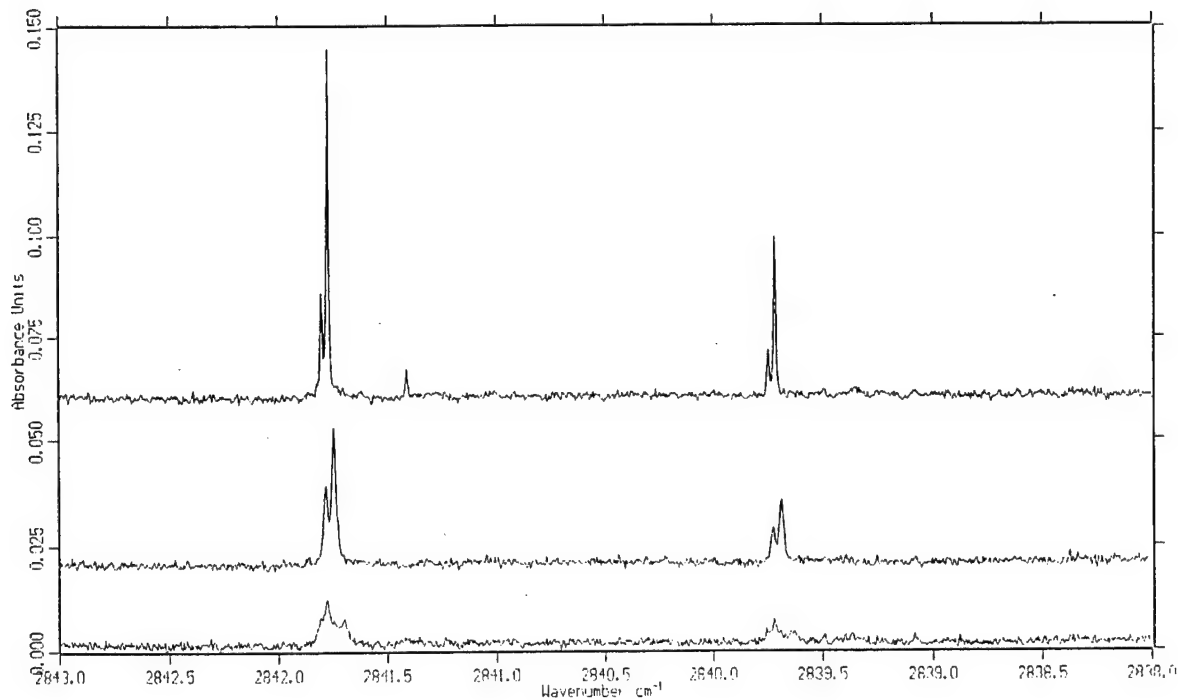
st27121.9
st27121.7
st27121.5

annealed T=2.4K
annealing T=4.8K
as deposited T=2.4K

resolution = 0.005 cm⁻¹

ST27121.5

HF-HCl/pH₂



st27121.9
st27121.7
st27121.5

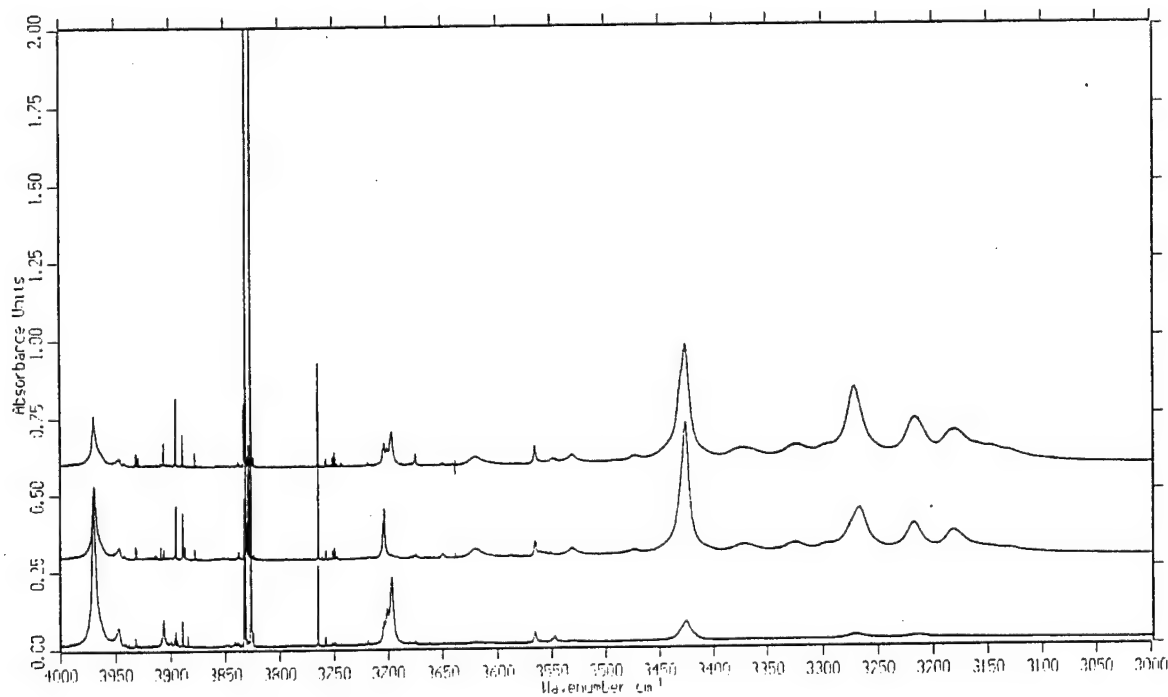
annealed T=2.4K
annealing T=4.8K
as deposited T=2.4K

27 PPM HF/pH₂ d≈3mm

resolution = 0.005 cm⁻¹

st27121.5

91 ^{ppm} PPM HF/pH₂ d≈3mm



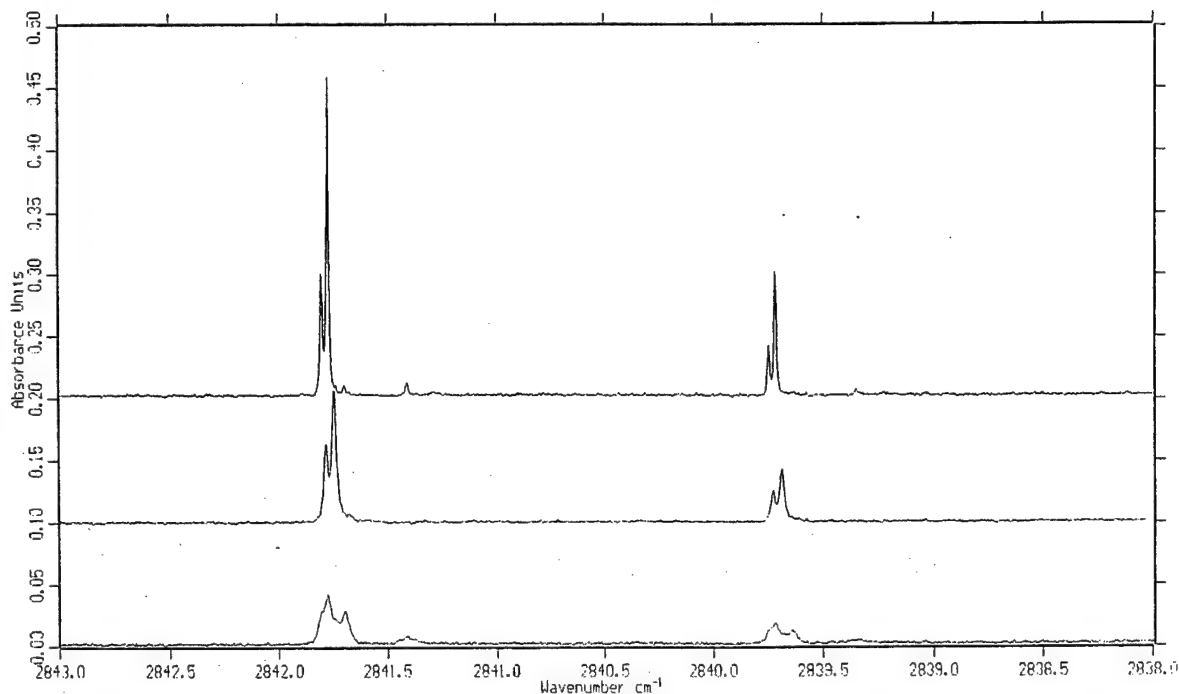
st27127.9
st27127.7
st27127.5

annealed T=2.4K
annealing T=4.8K
as deposited T=2.4K

resolution = 0.005 cm⁻¹

st27127.5

HF-HCl/pH₂



st27127.9
st27127.7
st27127.5

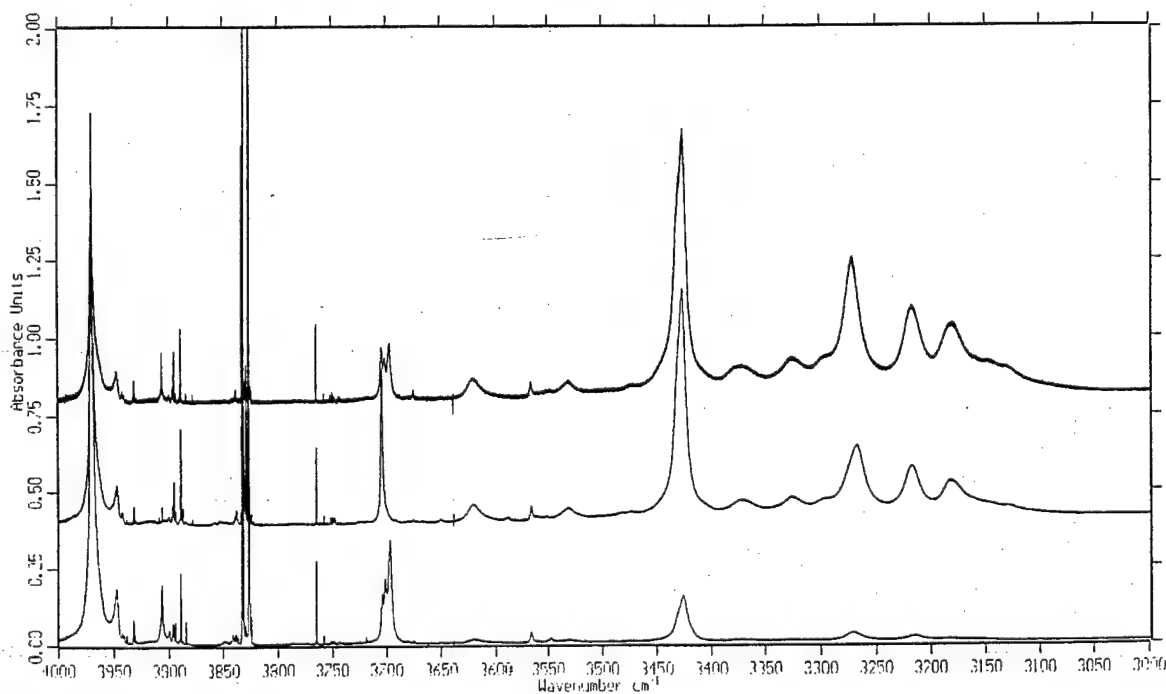
annealed T=2.4K
annealing T=4.8K
as deposited T=2.4K

91 PPM HF/pH₂ d≈3mm

resolution = 0.005 cm⁻¹

st27127.5

ppm 268 PPM HF/pH₂ d≈3mm



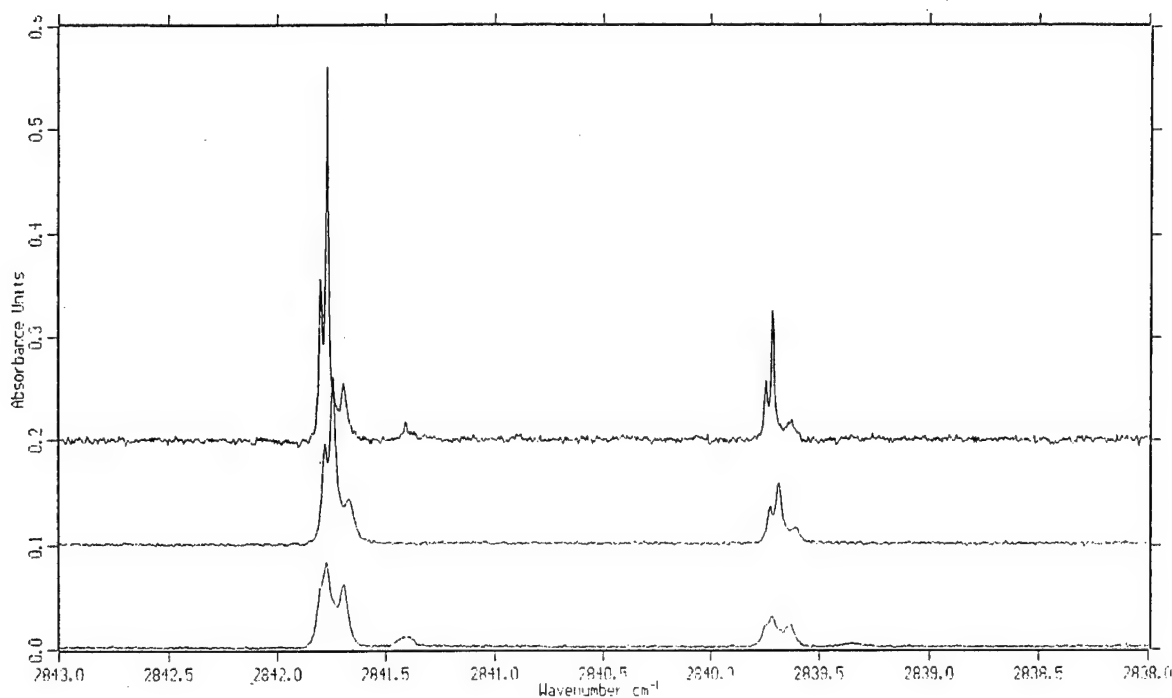
st27133.9
st27133.7
st27133.5

annealed T=2.4K
annealing T=4.8K
as deposited T=2.4K

resolution = 0.005 cm⁻¹

st27133.5

HF-HCl/pH₂



st27133.9
st27133.7
st27133.5

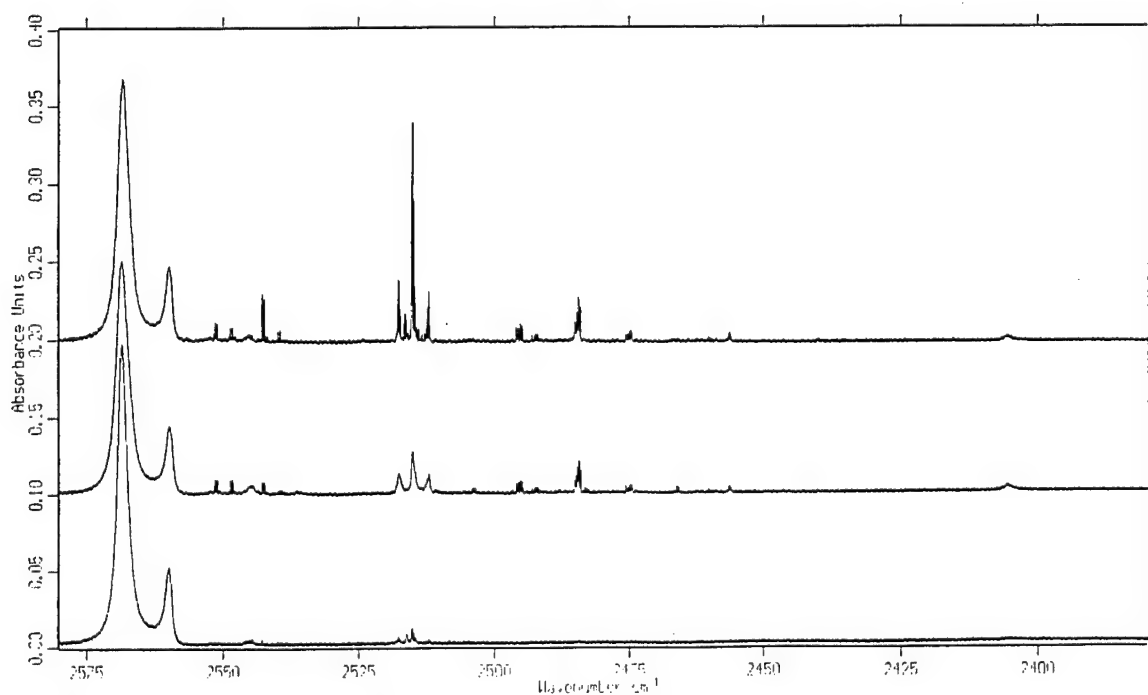
annealed T=2.4K
annealing T=4.8K
as deposited T=2.4K

268 PPM HF/pH₂ d≈3mm

resolution = 0.005 cm⁻¹

st27133.5

80 PPM HBr/pH₂ d≈3mm



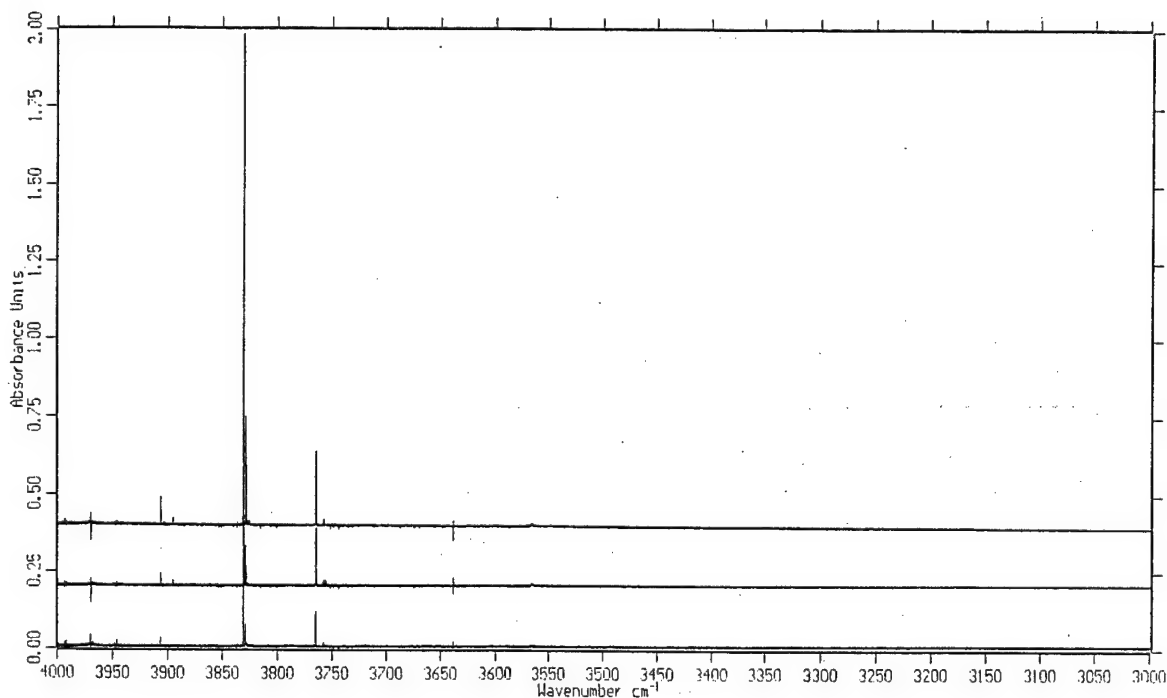
st27140.9
st27140.7
st27140.5

annealed T=2.4K
annealing T=4.8K
as deposited T=2.4K

resolution = 0.005 cm⁻¹

st27140.5

HF-(HF, HCl, HBr)/pH₂



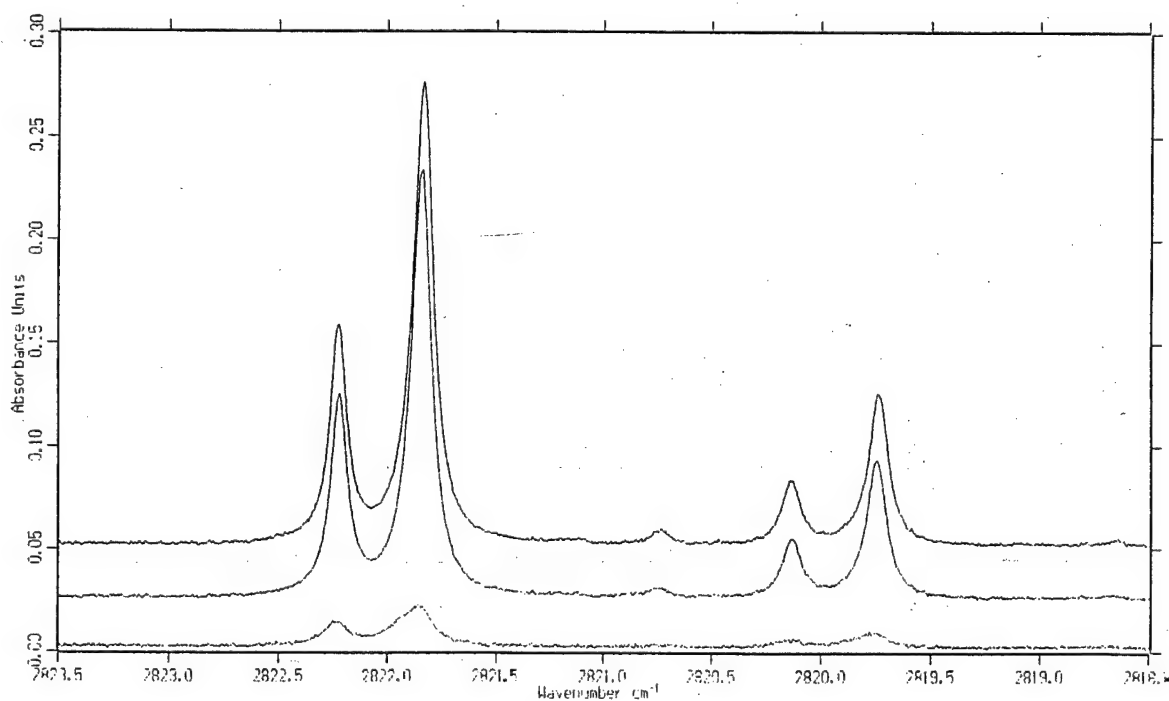
st27140.9 annealed T=2.4K
 st27140.7 annealing T=4.8K
 st27140.5 as deposited T=2.4K

80 PPM HBr/pH₂ d≈3mm

resolution = 0.005 cm⁻¹

st27140.5

HCl-HBr/pH₂



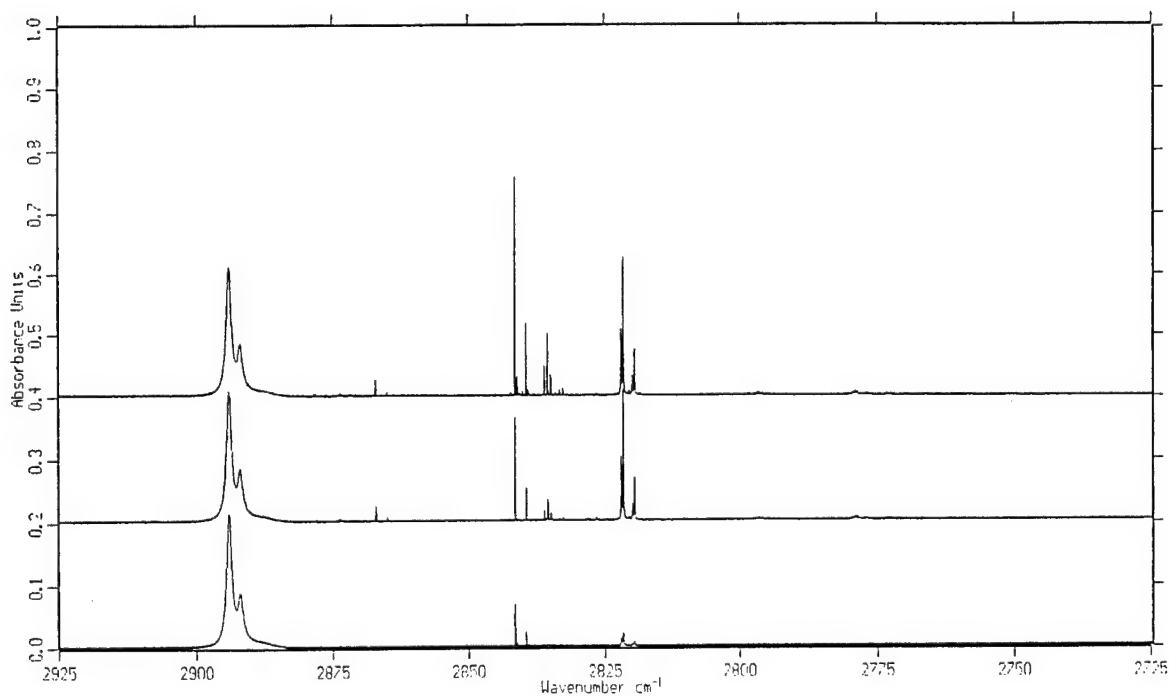
st27140.9 annealed T=2.4K
 st27140.7 annealing T=4.8K
 st27140.5 as deposited T=2.4K

80 PPM HBr/pH₂ d≈3mm

resolution = 0.005 cm⁻¹

st27140.5

HCl-(HF, HCl, HBr)/pH₂



st27140.9

annealed T=2.4K

st27140.7

annealing T=4.8K

st27140.5

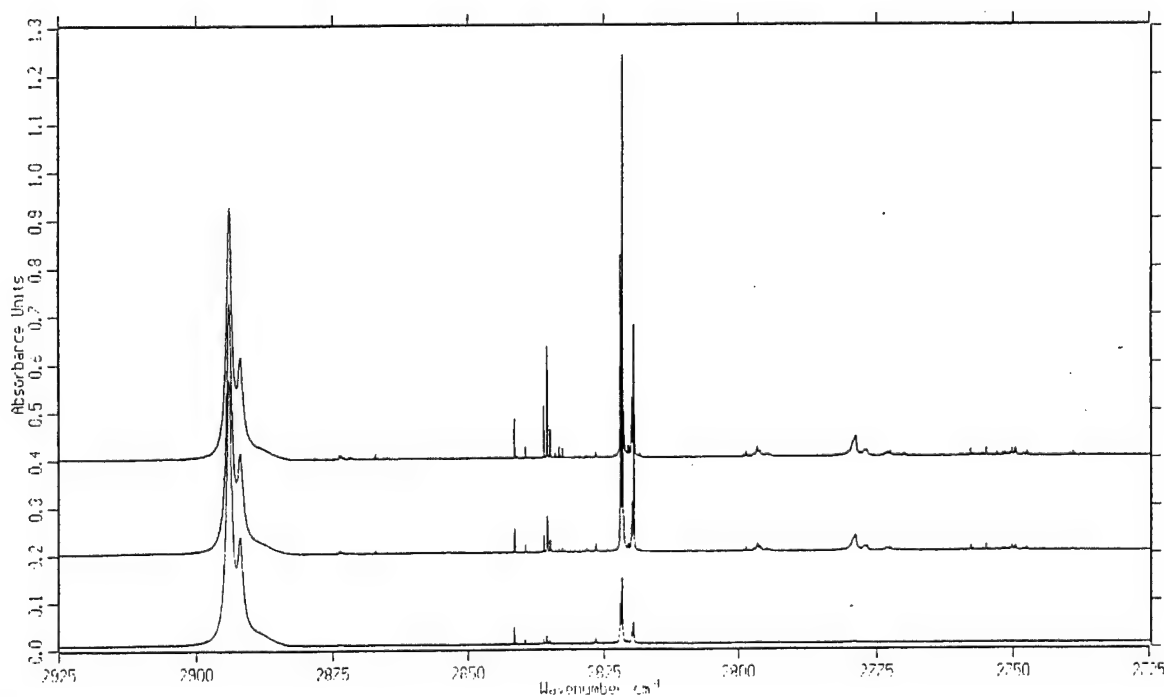
as deposited T=2.4K

80 PPM HBr/pH₂ d≈3mm

resolution = 0.005 cm⁻¹

st27140.5

HCl-(HF, HCl, HBr)/pH₂



st27145.9

annealed T=2.4K

st27145.7

annealing T=4.8K

st27145.5

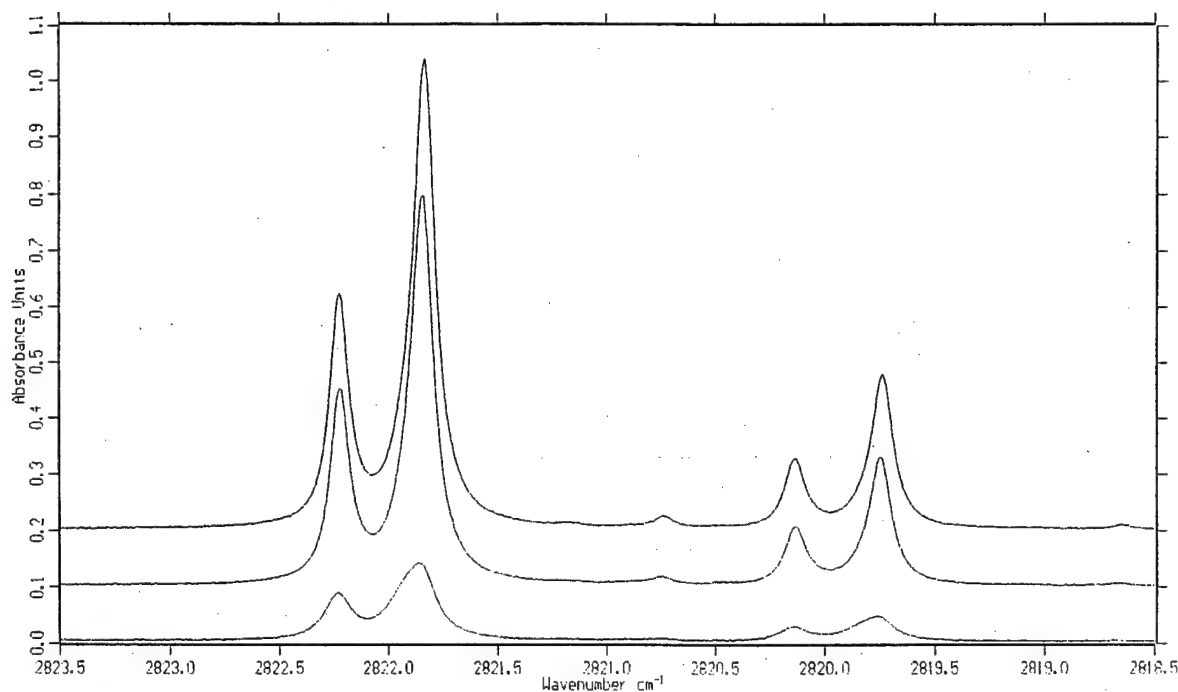
as deposited T=2.4K

260 PPM HBr/pH₂ d≈3mm

resolution = 0.005 cm⁻¹

st27145.5

HCl-HBr/pH₂



st27145.9
st27145.7
st27145.5

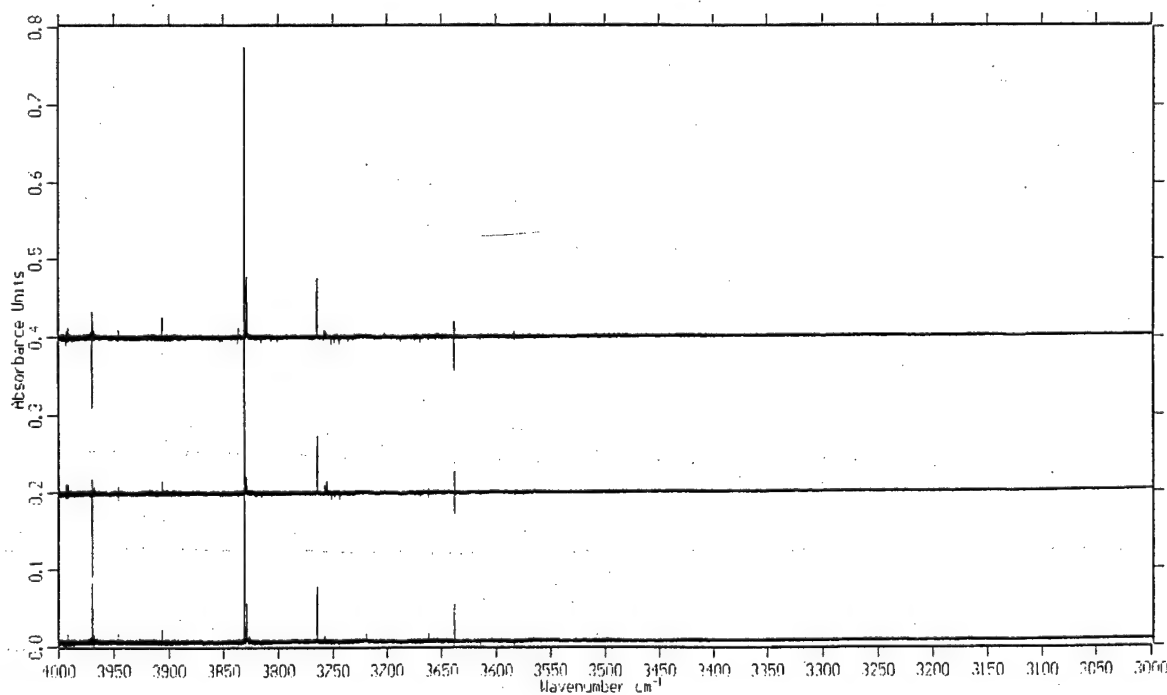
annealed T=2.4K
annealing T=4.8K
as deposited T=2.4K

250 PPM HBr/pH₂ d≈3mm

resolution = 0.005 cm⁻¹

ST27145.5

HF-(HF, HCl, HBr)/pH₂



st27145.9
st27145.7
st27145.5

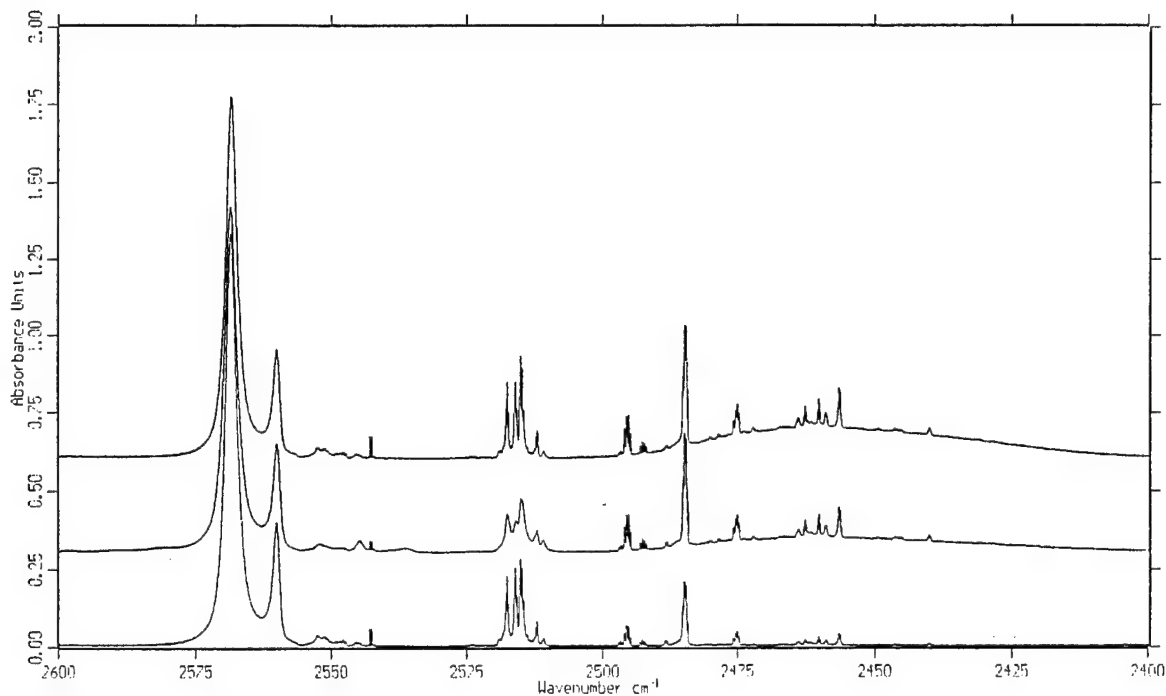
annealed T=2.4K
annealing T=4.8K
as deposited T=2.4K

260 PPM HBr/pH₂ d≈3mm

resolution = 0.005 cm⁻¹

ST27145.5

645 HBr/pH₂ d≈3mm

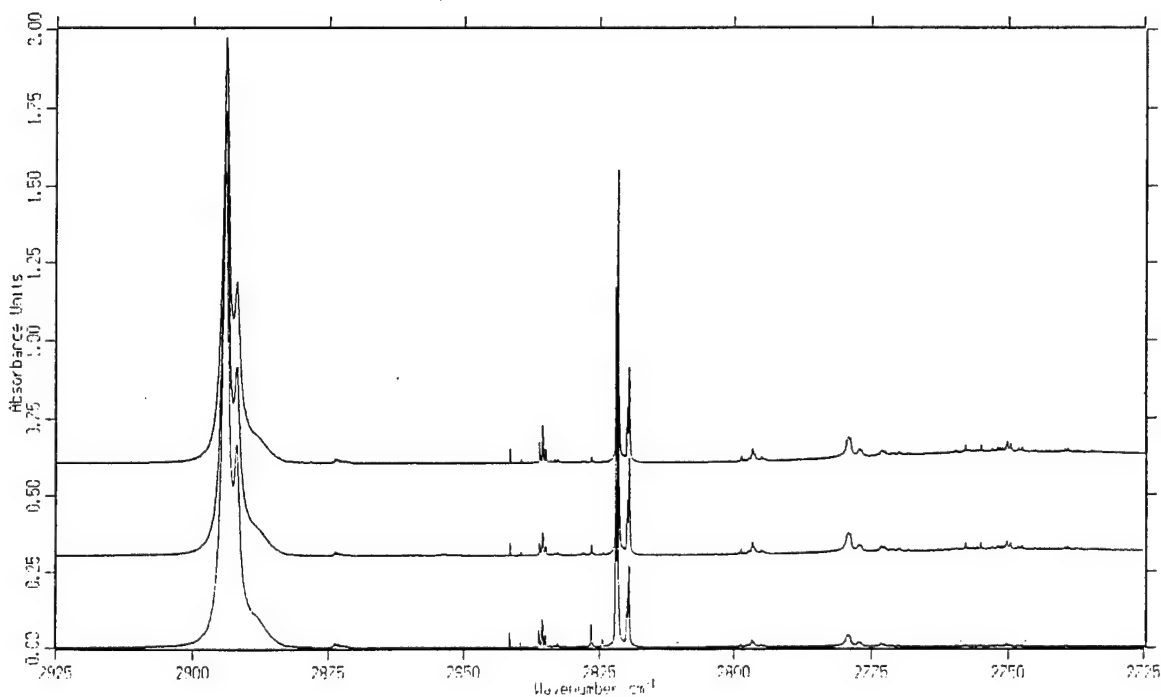


st28003.9 annealed T=2.4K
 st28003.7 annealing T=4.8K
 st28003.5 as deposited T=2.4K

resolution = 0.005 cm⁻¹

st28003.5

HCl(HBr)_n/pH₂

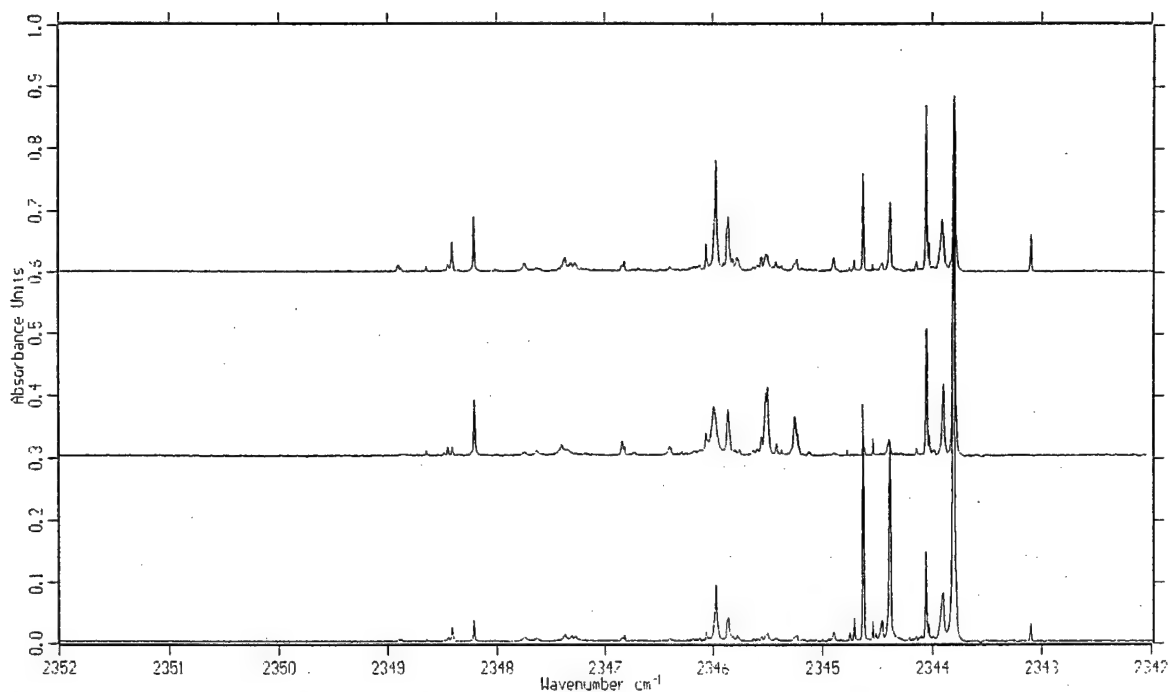


st28003.9 annealed T=2.4K
 st28003.7 annealing T=4.8K
 st28003.5 as deposited T=2.4K

645 HBr/pH₂ d≈3mm

resolution = 0.005 cm⁻¹

st28003.5



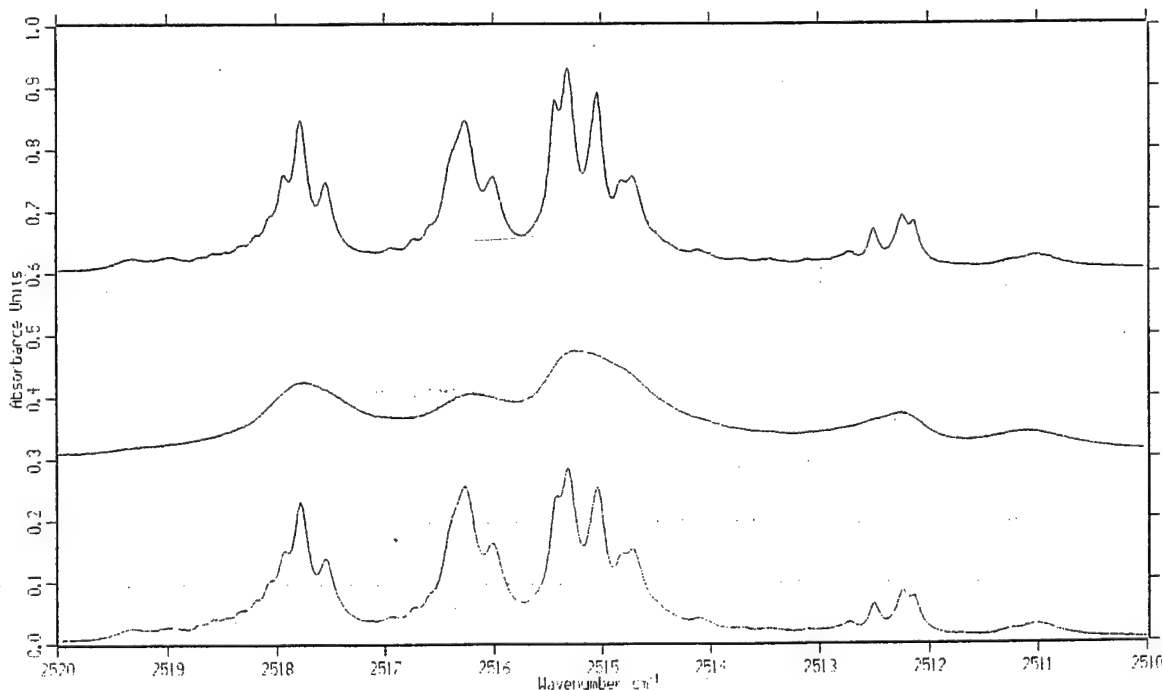
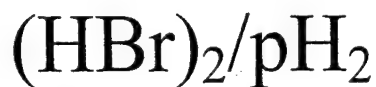
st28003.9
st28003.7
st28003.5

annealed $T=2.4\text{K}$
annealing $T=4.8\text{K}$
as deposited $T=2.4\text{K}$

645 HBr/ pH_2 $d \approx 3\text{mm}$

resolution = 0.005 cm^{-1}

ST28003.5



st28003.9
st28003.7
st28003.5

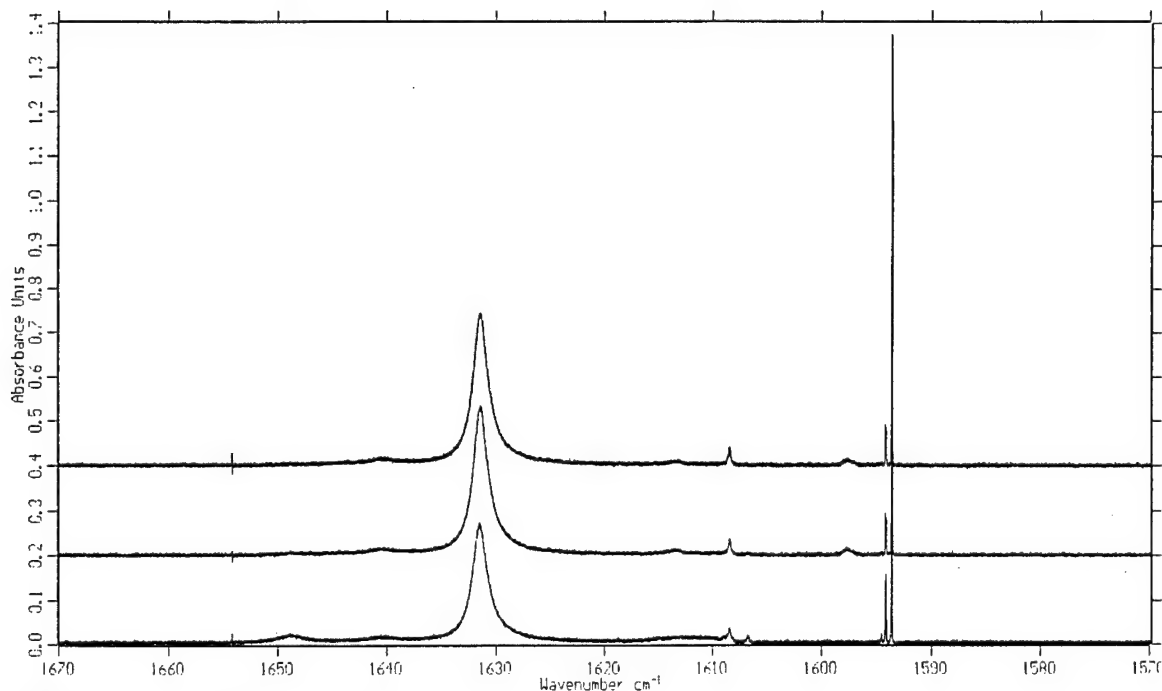
annealed $T=2.4\text{K}$
annealing $T=4.8\text{K}$
as deposited $T=2.4\text{K}$

645 HBr/ pH_2 $d \approx 3\text{mm}$

resolution = 0.005 cm^{-1}

ST28003.5

^{ppm}
15 ~~PPM~~ H₂O/pH₂ d≈3mm



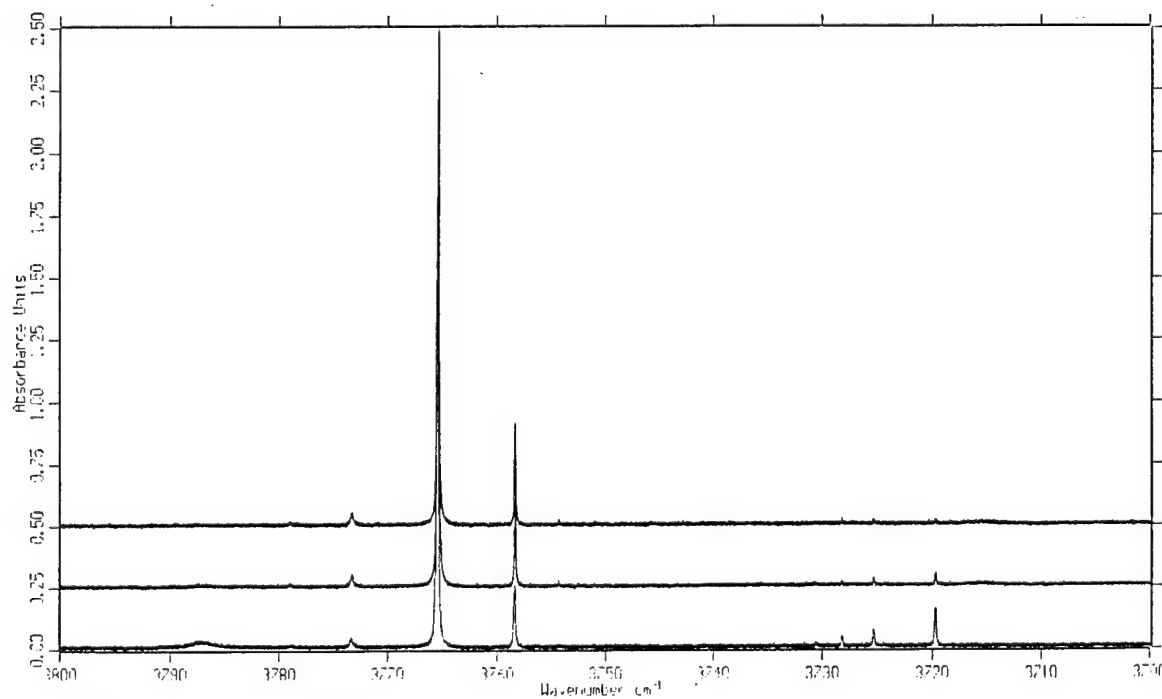
st28010.6
st28010.4
st28010.2

annealed T=2.4K
annealing T=4.8K
as deposited T=2.4K

resolution = 0.005 cm⁻¹

ST28010.2

^{ppm}
15 ~~PPM~~ H₂O/pH₂ d≈3mm



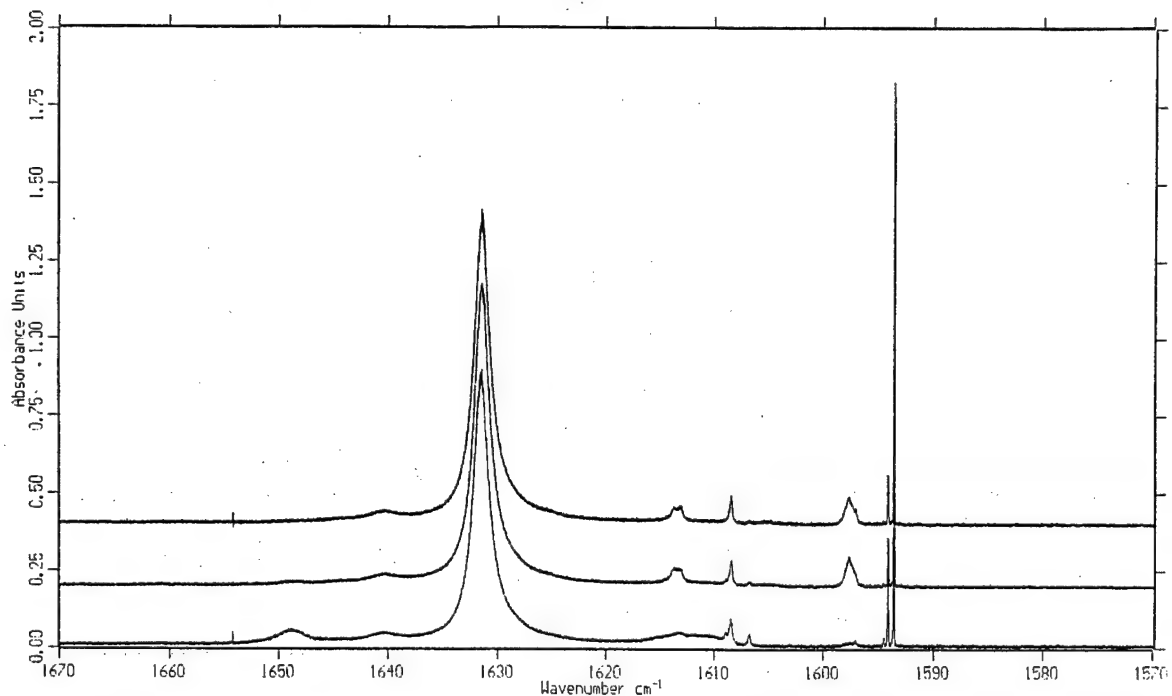
st28010.6
st28010.4
st28010.2

annealed T=2.4K
annealing T=4.8K
as deposited T=2.4K

resolution = 0.005 cm⁻¹

ST28010.2

ppm
45 PPM H₂O/pH₂ d₂≈3mm

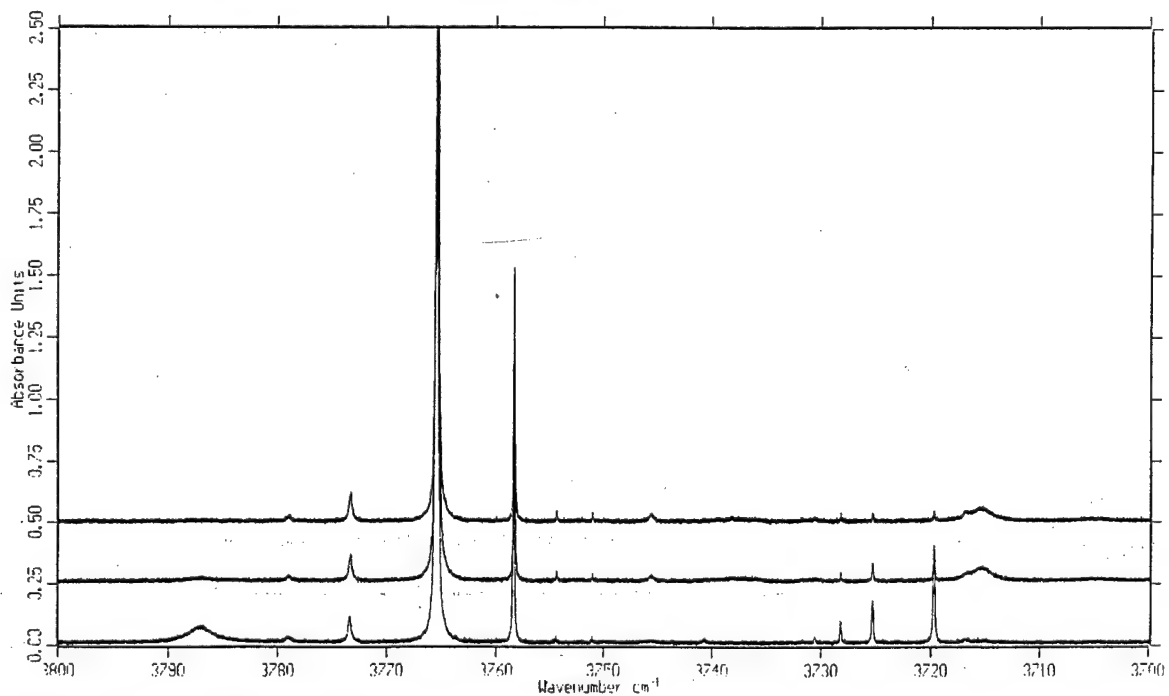


st28014.6 annealed T=2.4K
st28014.4 annealing T=4.8K
st28014.2 as deposited T=2.4K

resolution = 0.005 cm⁻¹

ST28014.2

ppm
45 PPM H₂O/pH₂ d₂≈3mm

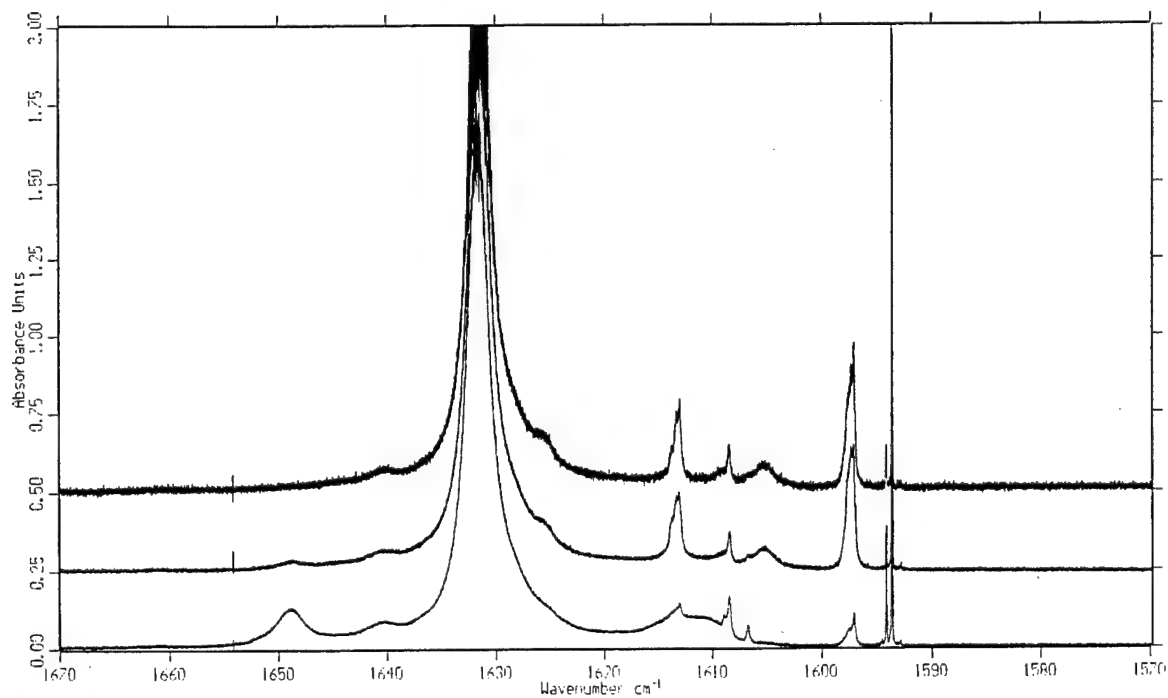


st28014.6 annealed T=2.4K
st28014.4 annealing T=4.8K
st28014.2 as deposited T=2.4K

resolution = 0.005 cm⁻¹

ST28014.2

ppm
138 PPM H₂O/pH₂ d≈3mm

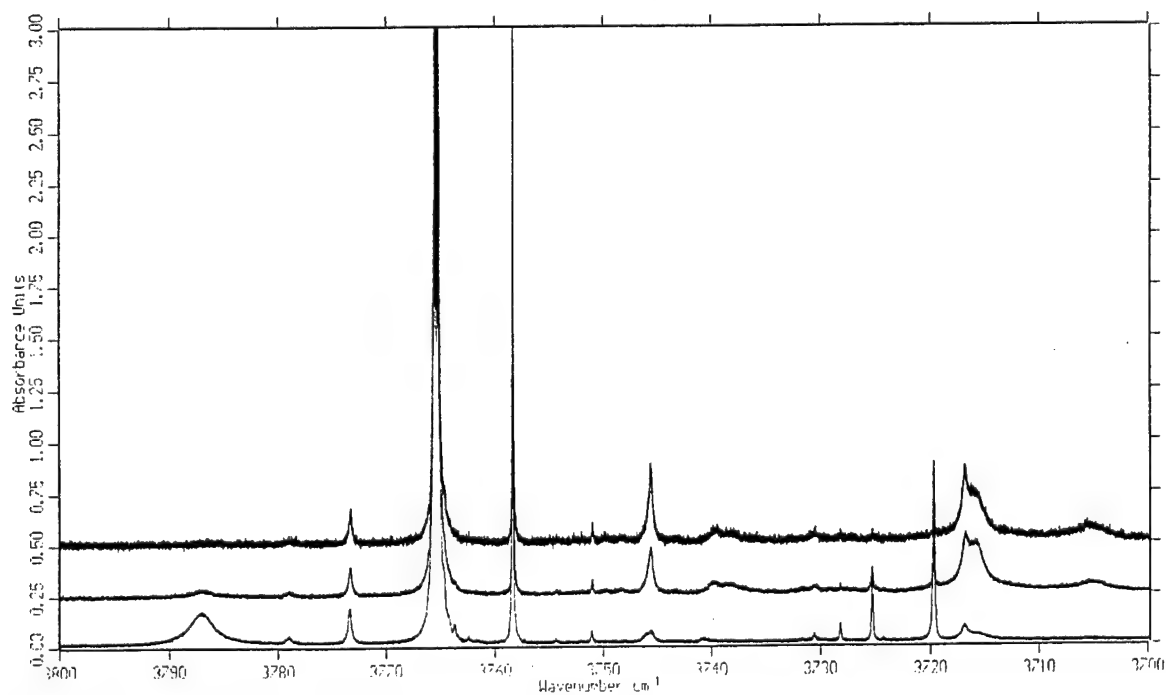


st28018.6 annealed T=2.4K
st28018.4 annealing T=4.8K
st28018.2 as deposited T=2.4K

resolution = 0.005 cm⁻¹

ST28018.2

ppm
138 PPM H₂O/pH₂ d≈3mm

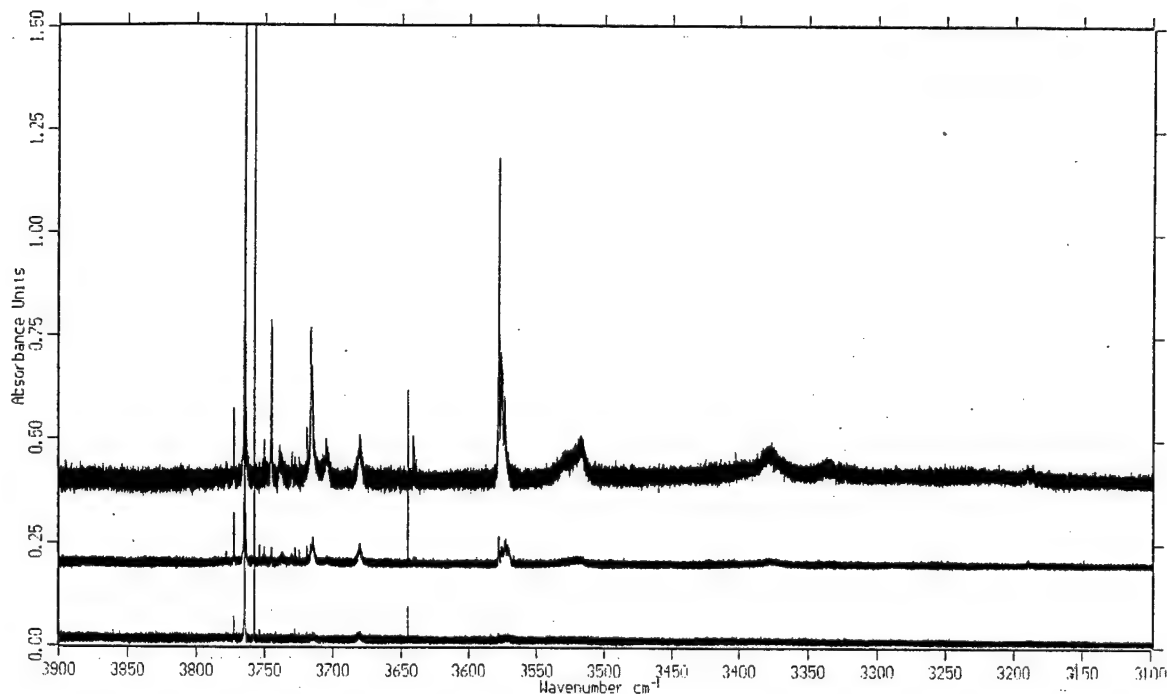


st28018.6 annealed T=2.4K
st28018.4 annealing T=4.8K
st28018.2 as deposited T=2.4K

resolution = 0.005 cm⁻¹

ST28018.2

H₂O clusters in pH₂

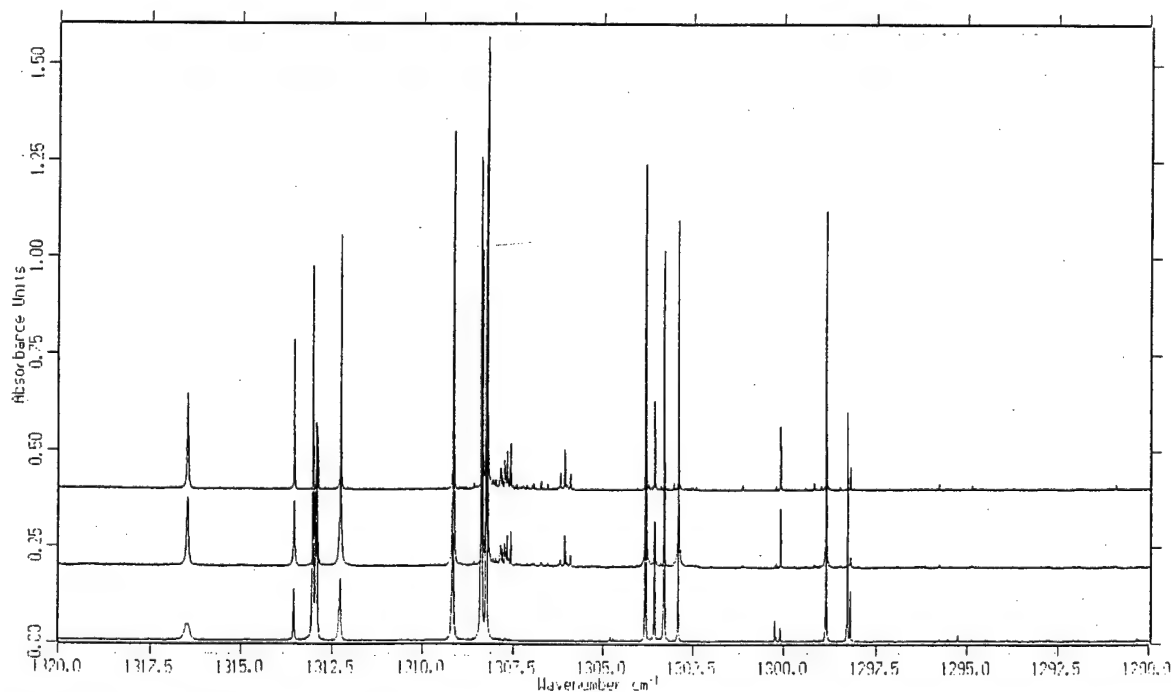


st28018.6 annealed T=2.4K 138 PPM H₂O/pH₂
 st28014.6 annealed T=2.4K 45 PPM H₂O/pH₂
 st28010.6 annealed T=2.4K 15 PPM H₂O/pH₂

resolution = 0.005 cm⁻¹

ST20010.6

56 ^{ppm} PPM CH₄/pH₂ d_z ≈ 0.7mm

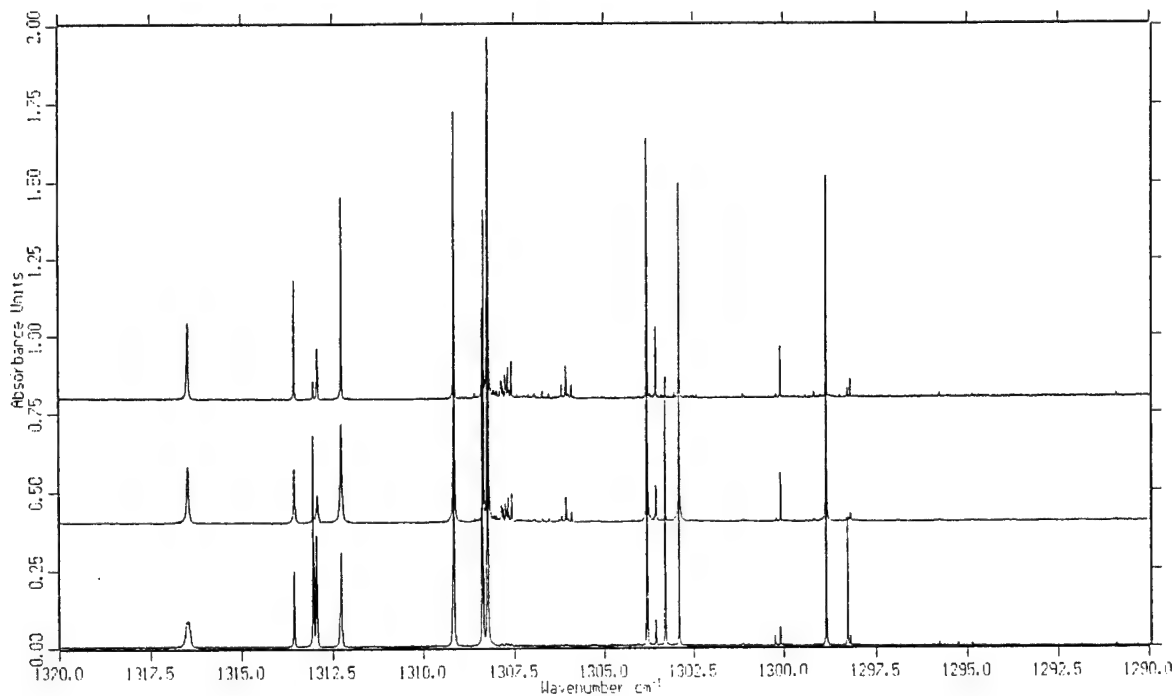


st28022.20 annealed T=2.4K
 st28022.19 annealing T=4.8K
 st28022.18 as deposited T=2.4K

resolution = 0.005 cm⁻¹

ST20010.6

ppm
200 PPM CH₄/pH₂ d≈0.2mm

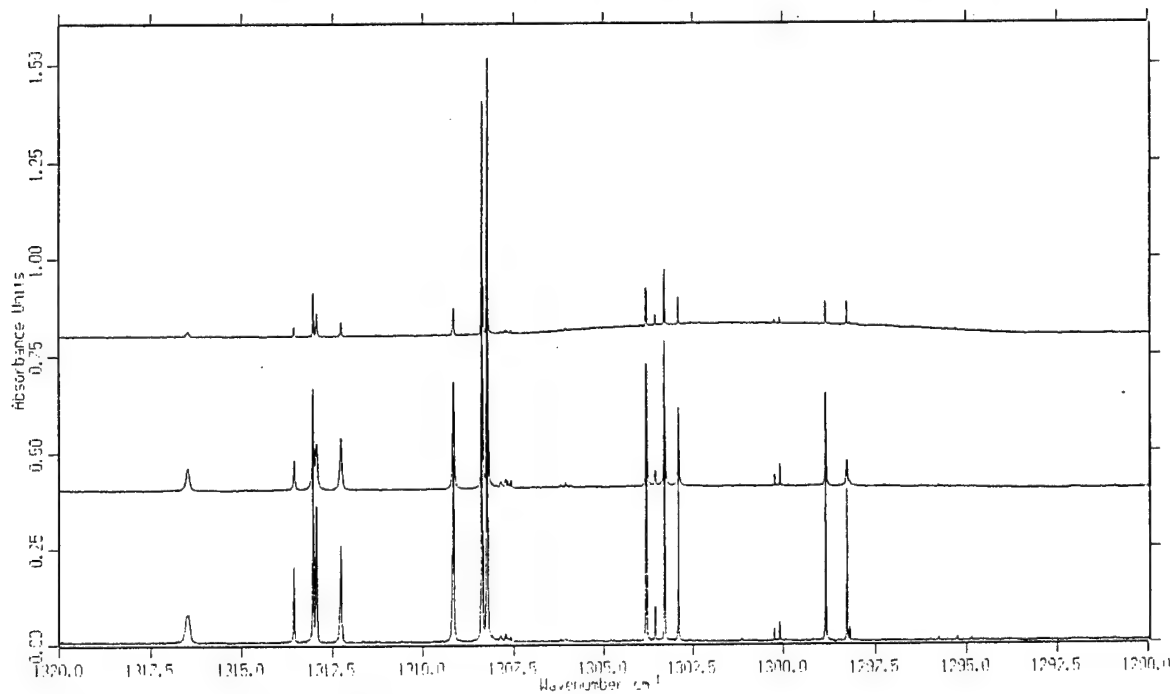


st28026.21 annealed T=2.4K
st28026.20 annealing T=4.8K
st28026.19 as deposited T=2.4K

resolution = 0.005 cm⁻¹

ST28026.19

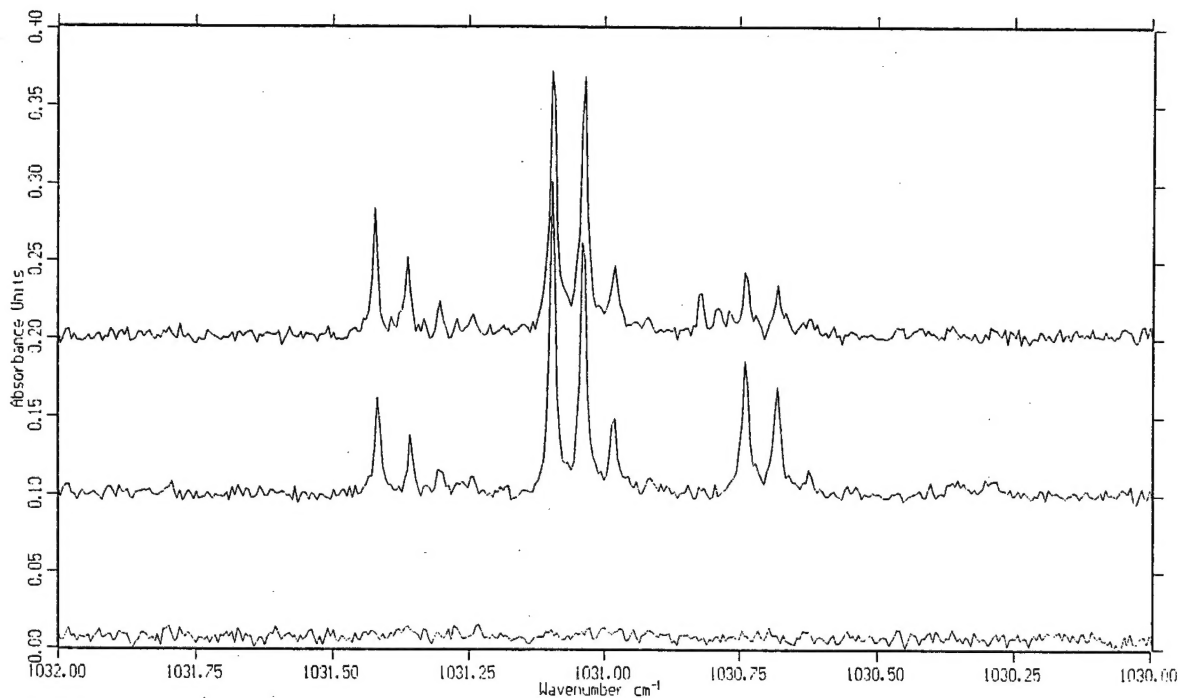
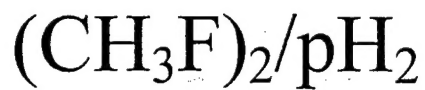
ppm
550 PPM CH₄/pH₂ d≈0.05mm



st28030.14 annealed T=2.4K
st28030.13 annealing T=4.8K
st28030.12 as deposited T=2.4K

resolution = 0.005 cm⁻¹

ST28030.1

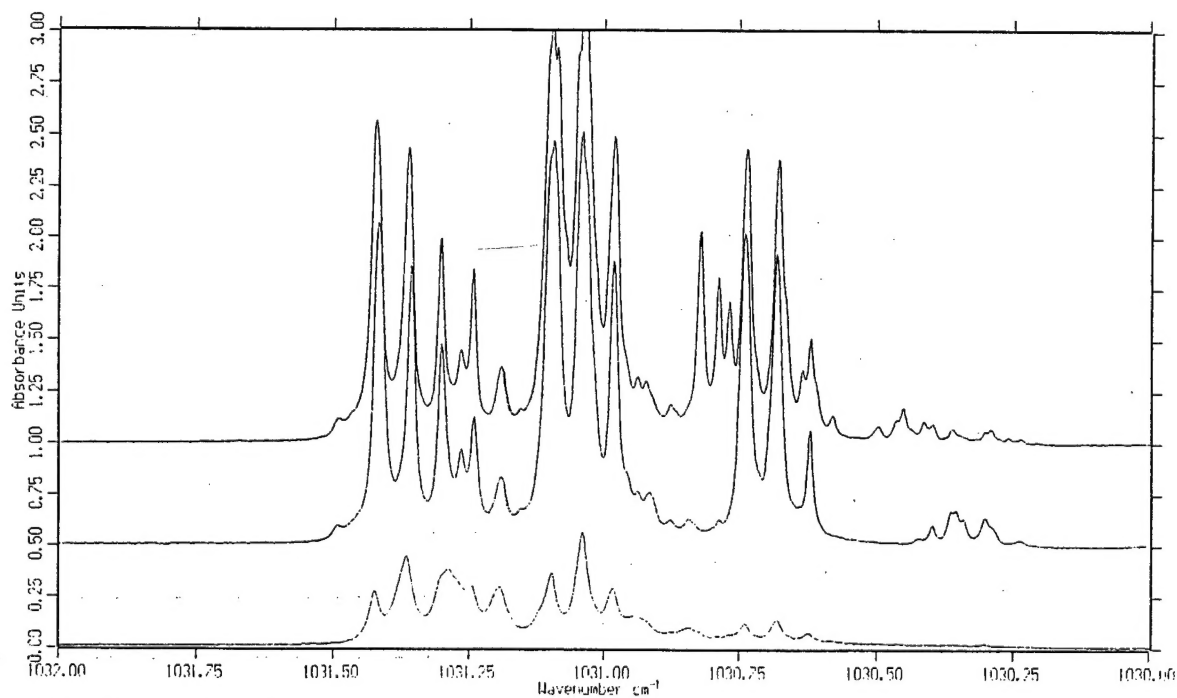
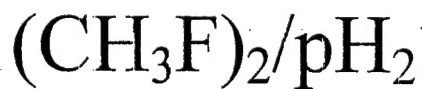


st28039.11 annealed T=2.4K
 st28039.9 annealing T=4.8K
 st28039.5 as deposited T=2.4K

10 PPM $\text{CH}_3\text{F}/\text{pH}_2$

resolution = 0.005 cm^{-1}

ST28039.5



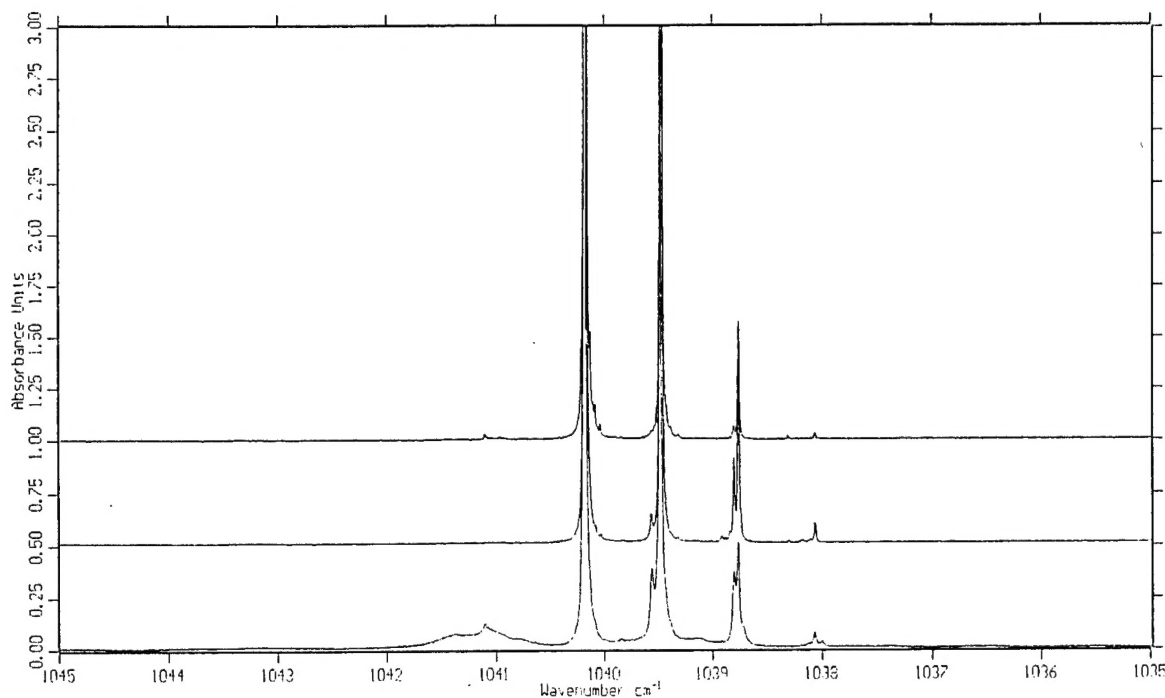
st28048.11 annealed T=2.4K
 st28048.7 annealing T=4.8K
 st28048.3 as deposited T=2.4K

91 PPM $\text{CH}_3\text{F}/\text{pH}_2$

resolution = 0.005 cm^{-1}

ST28048.3

^{ppm}
6 PPM CH₃F/pH₂ d≈3mm

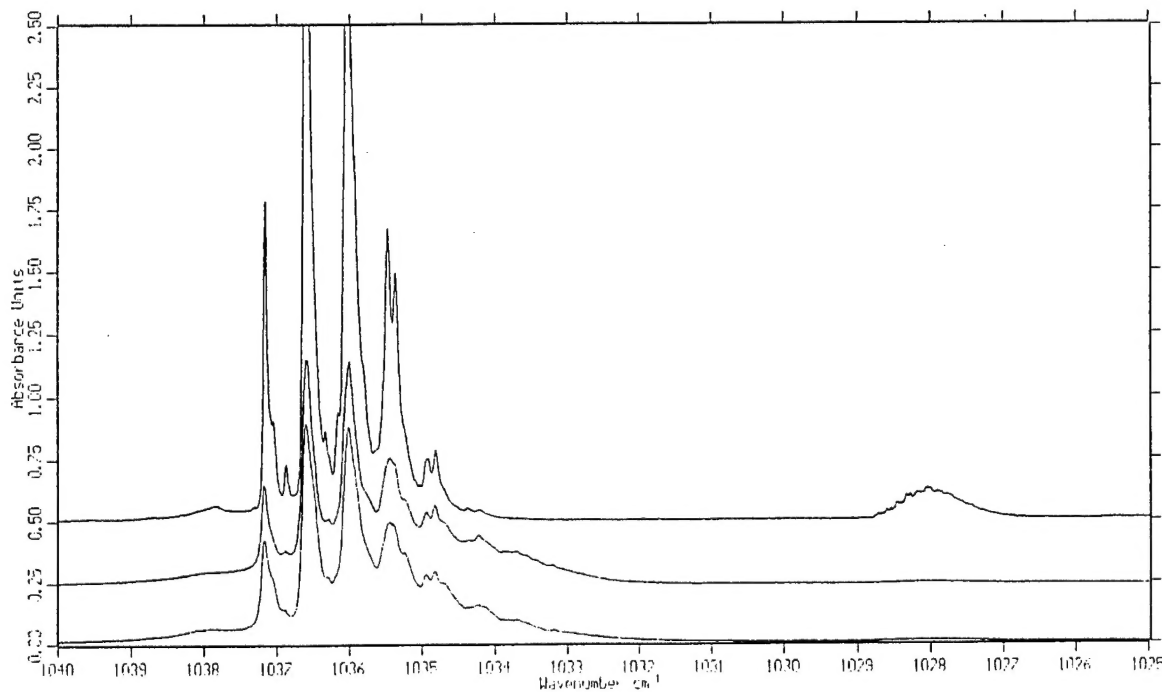


st28052.10 annealed T=2.4K
st28052.6 annealing T=4.8K
st28052.2 as deposited T=2.4K

resolution = 0.005 cm⁻¹

ST28052.2

^{ppm}
33 PPM CH₃F/oD₂ d≈2mm

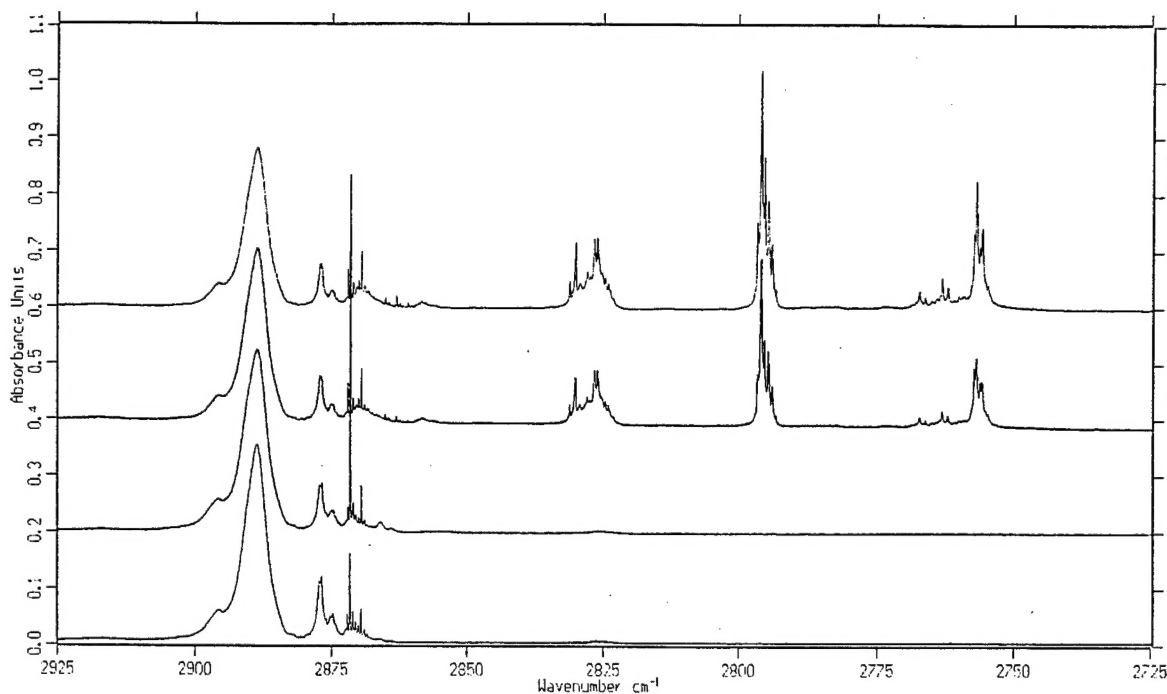


st28073.11 flash annealed to 10K T=2.4K
st28073.7 annealing T=4.8K
st28073.3 as deposited T=2.4K

resolution = 0.005 cm⁻¹

ST28073.3

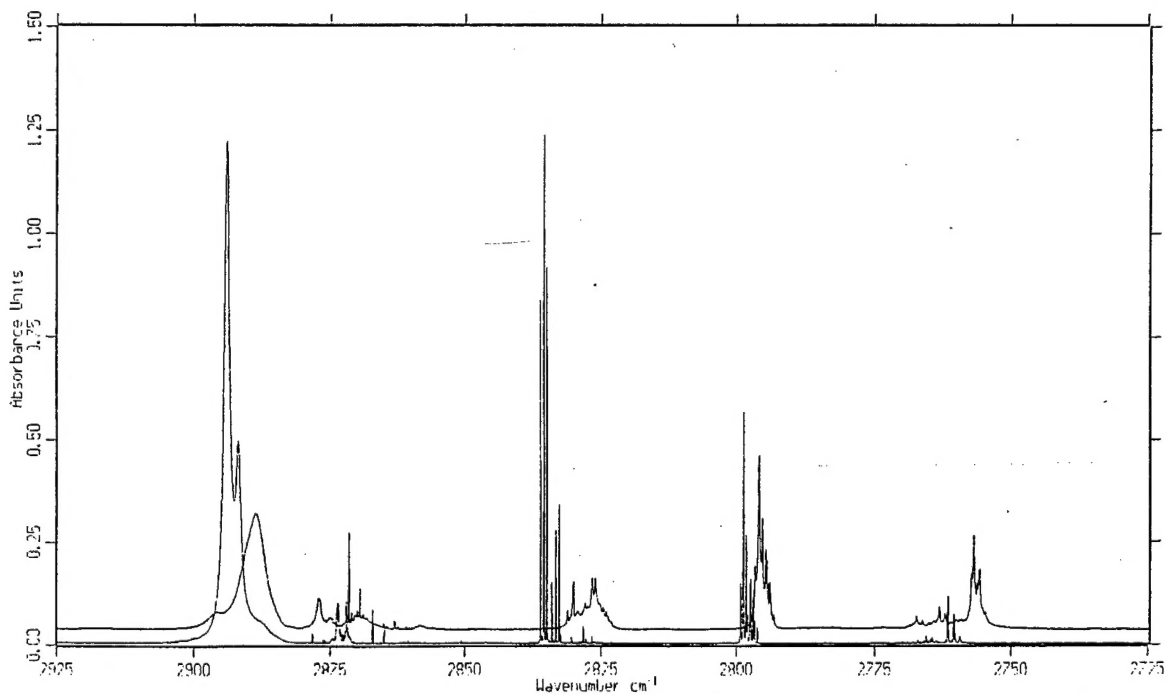
ppm
93 PPM HCl/oD₂ d≈2mm



st28079.7 2nd flash annealing T=2.4K st28079.3 annealing T=4.8K
st28079.5 flash annealed to 10K T=2.4K st28079.1 as deposited T=2.4K resolution = 0.005 cm⁻¹

ST28079.1

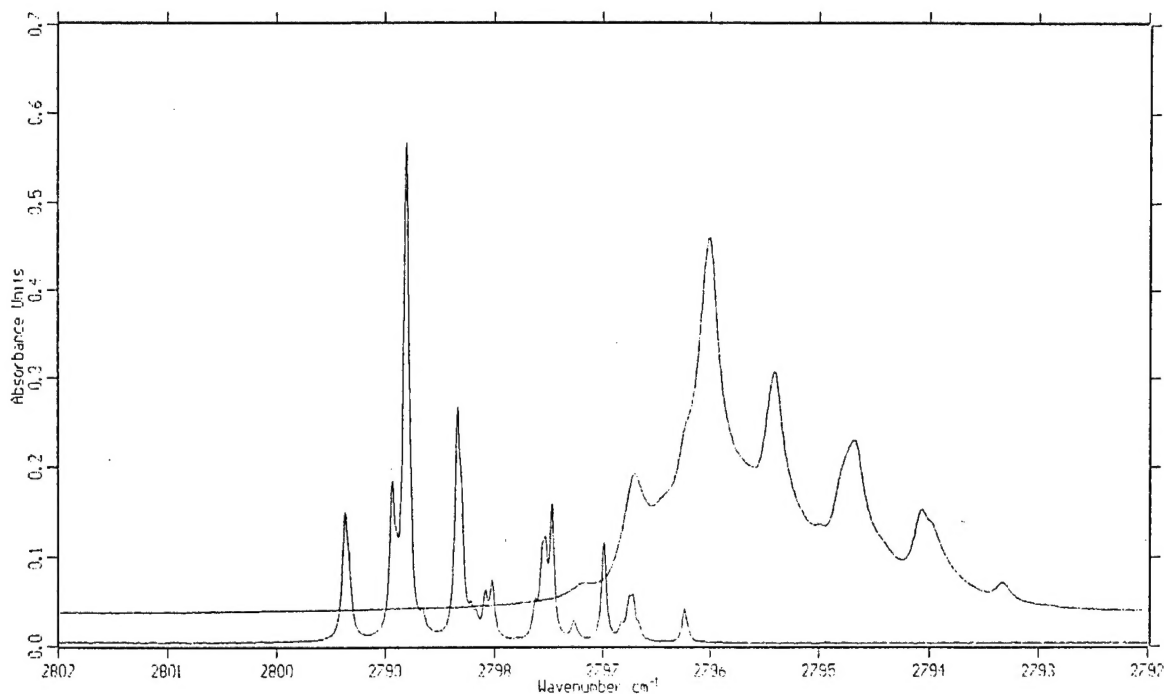
HCl/pH₂ vs. HCl/oD₂



st28079.7 annealed T=2.4K 93 PPM HCl/oD₂ (≈98%)
st27061.11 annealed T=2.4K 88 PPM HCl/pH₂ (99.99+%)

ST27061.11

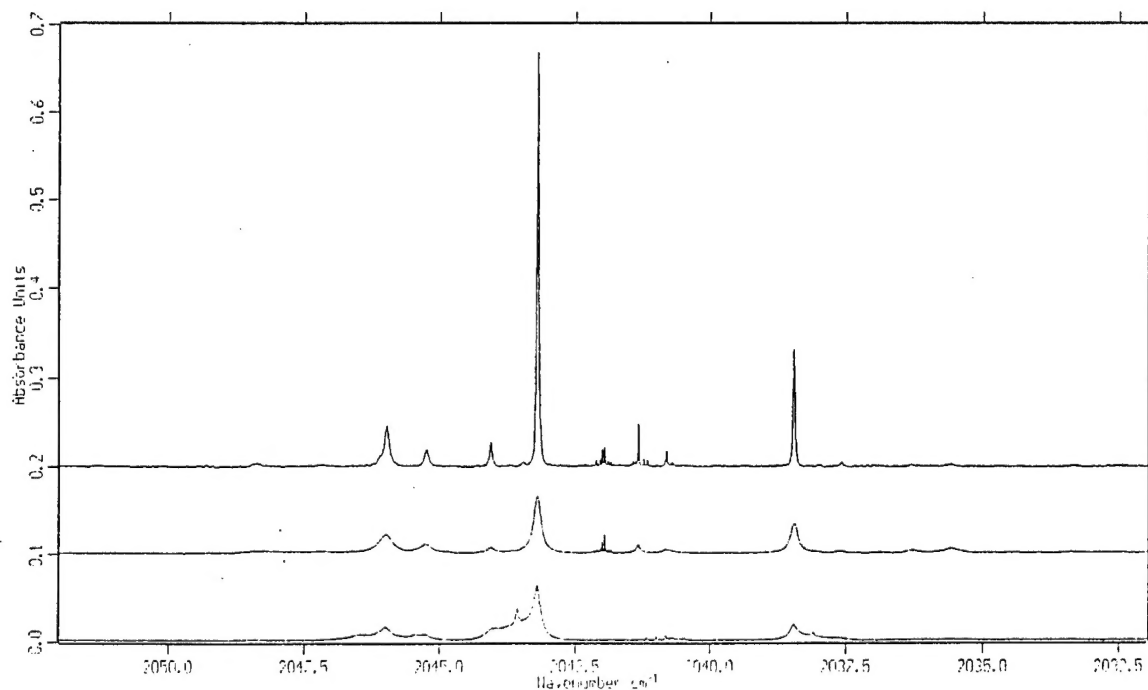
$(\text{HCl})_3/\text{pH}_2$ & $(\text{HCl})_3/\text{oD}_2$



st28079.7 annealed T=2.4K 93 PPM HCl/oD_2 ($\approx 98\%$)
 st27061.11 annealed T=2.4K 88 PPM HCl/pH_2 (99.99+%)

st27061.11

$^{13}\text{C}^{18}\text{O}/\text{pH}_2$ $d \approx 3\text{mm}$



st28082.6 annealed T=2.4K
 st28082.4 annealing T=4.8K
 st28082.2 as deposited T=2.4K

11 PPM $^{13}\text{C}/\text{pH}_2$ resolution = 0.005 cm^{-1}

st28082.2